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Environmental Impact Research Program

Survey of Habitat-Related Channel Features and Structures in Tailwaters

by *Katherine S. Long, John M. Nestler, J. Craig Fischenich*

Prepared for Headquarters, U.S. Army Corps of Engineers

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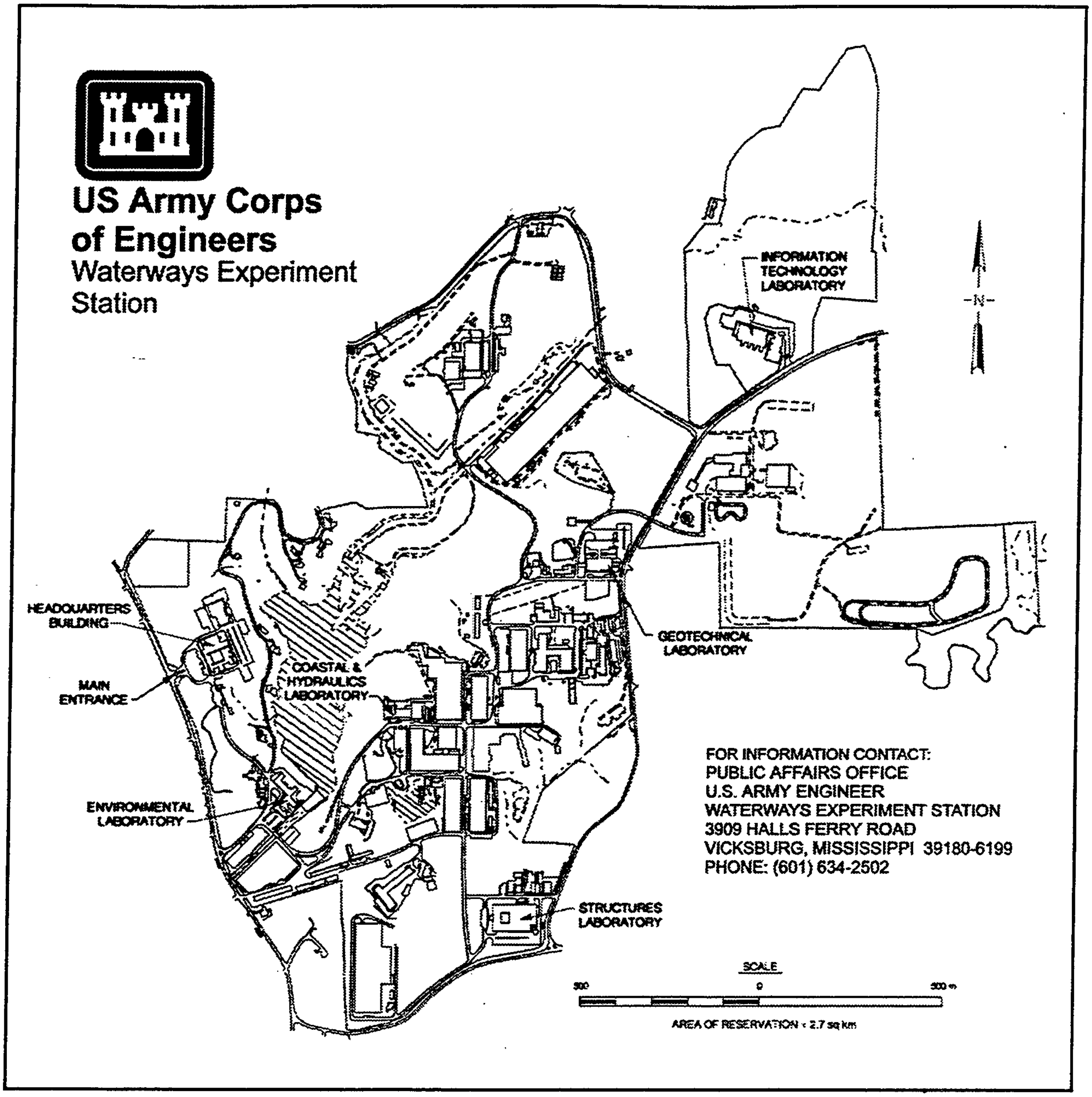

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US Army Corps of Engineers
Waterways Experiment Station

Environmental Impact Research Program

Assessing Benefits of Channel Modification for Aquatic Habitat in Tailwaters and Local Flood Control Channels

Summary of Habitat-Related Channel Features and Structures in Tailwaters (TR EL-97-6)

ISSUE: Corps of Engineers activities and regulatory decisions can affect habitat quality in stream ecosystems. Habitat quality is dependent on water quality, bed slope, water temperature, substrate, vegetation, and hydraulic parameters in streams. Regulated streams often exhibit degraded habitat conditions because impoundment or water diversion may alter chemical, physical, and biotic variables affecting habitat quality. A variety of tools are available to assess habitat quality in streams, and these assessments can be the basis of remedial actions to reduce or mitigate the impact of stream regulation. Presently, application guidance for different assessment tools is unavailable, and a compendium of methods for improving stream habitat suitable for larger stream systems such as are commonly encountered below dams is also unavailable.

RESEARCH OBJECTIVE: The objectives of this report are to (a) identify and describe habitat assessment methods that can be used for tailwaters and (b) identify and describe structures and habitat features that can be used to improve habitat quality in tailwaters or similar-sized streams exhibiting degraded habitat quality.

SUMMARY: This report surveys past, present, and planned modifications of tailwaters used by agencies including the Corps of Engineers, Tennessee Valley Authority, and Bureau of Reclamation attempting to improve stream habitat quality. Tables are included that describe the modification and identify the target aquatic organisms for which the modifications were designed. Assessments of the efficacy of the modifications are presented as the methods used to evaluate the effectiveness of the modifications.

AVAILABILITY: The report is available on Interlibrary Loan Service from the U.S. Army Engineer Waterways Experiment Station (WES) Library, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199; telephone (601) 634-2355. To purchase a copy, call the National Technical Information Service (NTIS) at (703) 487-4650. For help in identifying a title for sale, call (703) 487-4780. NTIS numbers may also be requested from the WES librarians.

About the Authors: The report was written by Ms. Katherine S. Long, Dr. John M. Nestler, and Dr. J. Craig Fischenich of the WES Environmental Laboratory. **Point of contact** is Dr. Nestler, WES, telephone (601) 634-3870.

Contents

Preface

The work described in this report was authorized by Headquarters, U.S. Army Corps of Engineers (HQUSACE), for publication in the Environmental Impact Research Program (EIRP), Work Unit 32698, "Assessing Benefits of Channel Modification for Aquatic Habitat in Tailwaters and Local Flood Control Channels." The work was performed by personnel of the Environmental Laboratory (EL), U.S. Army Engineer Waterways Experiment Station (WES), and is a survey of habitat-related channel features and structures in tailwaters.

Principal Investigator was Dr. John M. Nestler, Water Quality and Contaminant Modeling Branch (WQCMB), Ecosystem Processes and Effects Division (EPED), EL, under the general supervision of Dr. Mark S. Dortch, Chief, WQCMB.

Dr. John Bushman, Mr. Frederick B. Juhle, and Mr. Dave Mathis were HQUSACE Technical Monitors for the EIRP. Dr. Russell F. Theriot, EL, is the Program Manager for the EIRP.

This report was written by Ms. Katherine S. Long, Ecosystem Processes and Effects Branch (EPEB), EL, under the direct supervision of Dr. Richard E. Price, Acting Chief, EPED, by Dr. Nestler under the direct supervision of Dr. Dortch, Chief, WQCMB, and by Mr. J. Craig Fischenich, Environmental Resources Engineering Branch, Environmental Engineering Division (EED), EL, under the direct supervision of Mr. Norman R. Francingues, Chief, EED. Dr. John W. Keeley, Assistant Director, EL, and Dr. John Harrison, Director, EL, provided general supervision. Inhouse technical review was performed by Mses. D. H. Tillman and L. T. Schneider, WQCMB.

The authors acknowledge the special cooperation of personnel of the Tennessee Valley Authority, the various U.S. Army Corps of Engineers Districts, and the Department of the Interior Bureau of Reclamation for sharing their relevant experiences and for providing literature on the subject study.

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Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
Fahrenheit degrees	5/9	Celsius degrees or kelvins[1]
feet	0.3048	meters
inches	2.54	centimeters
miles (U.S. statute)	1.609347	kilometers
pounds	0.4535924	kilograms

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: C = (5/9) (F-32). To obtain kelvin (K) readings, use the following formula: K = (5/9) (F-32) + 273.15.

1 Introduction

Statement of Problem

Reservoir tailwaters and local flood control channels are often characterized by degraded physical habitat and water quality. Local flood control channels may provide little or no physical habitat during low-flow periods because of reduced diversity of physical conditions in the channel, lack of water, or elevated water temperatures resulting from removal of riparian vegetation. Similarly, reservoir operation may result in considerable alterations in flow and water quality conditions from those present before impoundment, particularly for peaking hydropower operations. In peaking hydropower operations, daily flow extremes may exceed monthly flow extremes in unregulated systems, resulting in tailwater commonly possessing potentially lethal saturations of dissolved gases as well as exceedingly high or low flows of a rhythm completely different from preimpoundment conditions of the stream(s).

In contrast, unregulated streams support healthy aquatic ecosystems due largely to their habitat complexity, benign water quality conditions, and regular hydrological patterns. Alternate pools and riffles, sinuous planforms, eroding banks, overhanging vegetation, boulders, logs, and variable substrate all contribute to physical habitat diversity within and along the channel. Low dissolved-oxygen concentrations are seldom encountered because of stream reaeration; consequently, many aquatic organisms in flowing water systems require high dissolved-oxygen levels. Constant stream aeration also prevents buildups of high concentrations of reduced chemical compounds that may be toxic to aquatic biota. Flow patterns in unregulated systems are life history patterns of many aquatic biota, tied to seasonal patterns in streamflow.

Although the direct and indirect effects of changes in streamflow regime on aquatic biota receive emphasis and examination, an important constraint is that the intended purpose(s) of the structure (dam, flood channel) should be compromised but minimally while diminishing its adverse effects on the aquatic habitat. Aquatic habitat quality that can be achieved with minimal changes in dam operation or flood channel design must be defined for each situation, context, and structure—no assumptions of "best" solutions, no techniques or measures readily translatable to all projects without additional investigation.

Reservoir dissolved oxygen (DO) depends upon the balance of oxygen producers with oxygen consumers. Contributing to DO are photosynthetic plants and algae in the reservoir and the atmosphere; reducing the level of DO are the processes of decomposition of organic substances, plant respiration, and nitrification. The balance between producers and consumers is dependent on such variables as temperature, contact with atmosphere and sediments, nutrients available for plants, solar radiation, and toxicants. Should the consumption of DO exceed the output of the producers, a reservoir will have low DO, and its tailwater will have depressed DO, depending upon how (from what depth, at what rate, etc.) the water is released from the reservoir. Many tailwaters in the United States have observably deficient DO (Bohac and Ruane 1991).

Low DO in tailwaters has been reported by the Tennessee Valley Authority (TVA), the Corps of Engineers (CE), and the Bureau of Reclamation (BOR). TVA reported a greater concern with DO in the summer, in the eastern United States, and at larger hydroelectric projects (greater than 30 MW). CE reported only minor problems, and they were all in the southeastern United States. BOR reported few DO problems. Hydroelectric power projects appear to have a greater probability of affecting DO than do nonpower projects, since production of power consumes energy that otherwise would aerate releases. Moreover, hydroelectric power projects are more likely to release water from great depths where DO tends to be lower than at the surface (Bohac and Ruane 1991).

Walburg et al. (1981b) reviewed the often contradictory literature describing the effects of release waters on the tailwater environment and biota. The physical and chemical conditions found in tailwaters downstream from warmwater and coldwater discharge impoundments were compared and contrasted with those found in natural streams. Reservoir discharges were found to modify the physical, chemical, and biological characteristics of the stream ecosystem, with the physical and chemical characteristics in tailwaters primarily determined by the depth, volume, and schedule of water releases. Difference between tailwaters and natural streams is related to the type of reservoir and to the design and operation of outlet structures. The structure of the biotic community, which includes nonnative species adapted to the tailwater environment, reflects the existing physical and chemical conditions.

Water quality problems in tailwater areas are frequently related to water quality conditions in the reservoir. Of particular concern are elevated concentrations of sulfide and reduced metals, such as iron and manganese. Field investigations at Narrows Dam (Lake Greeson), on the Little Missouri River in southwest Arkansas, document temporal and spatial patterns in the distribution of sulfide and reduced metals within and below a hydropower reservoir. Laboratory experiments involving reaeration of anoxic hypolimnetic waters were conducted to evaluate factors influencing the oxidation of various reduced metals and were compared with field observations (Nix 1986).

Bohac and Ruane (1991) highlight some causes and concerns of low DO in releases from hydropower projects and describe the history of hydroturbine aeration for reaerating these releases. "All new proposals for hydropower development and many of the almost 300 hydroelectric projects which will be relicensed before 2000 will have to address the issue of minimum dissolved oxygen concentrations."

Stream regulation creates severe problems for aquatic organisms whose metabolic and physiological efficiencies and reproduction are closely attuned to specific thermal regimes. Fishes subjected to the unnatural thermal fluctuations associated with dams used for hydroelectric power exhibit an increase in genetic variation, resulting in a greater array of enzymes, changing their metabolic rate. Fish populations subjected to a constant but depressed thermal regime exhibit less genetic variation, an adaptive response to a more predictable environment. Species living in cooler tailwaters of hypolimnion-release dams also have depressed temperature preferences and critical thermal maxima. In addition, alteration of habitats and thermal regimes in the tailwaters of reservoirs often provides habitats and thermal cues for simultaneous reproduction in certain fish, resulting in an increase in hybridization events (Zimmerman 1984).

The parameters of special interest—water levels, temperature, and DO—conspicuously affected by structures impeding natural streamflow are most affected in the deep impoundments immediately upstream from the hydropower dams and in the tailwaters downstream. The altered quality becomes most conspicuous (and thus a matter of public concern) when fish are stressed downstream.

Many approaches to modeling water quality have been devised; although modeling natural lakes and streams is similar to modeling reservoirs, distinct and significant differences must be considered when selecting and applying a modeling approach to the water quality of a reservoir/tailwater scenario.

While reservoir-specific characteristics and behavior must be considered, thermal fluctuations, dissolved oxygen depletion, alternate substrate inundation and dewatering, and sluicing of sediments are among the additional stress factors to which tailwater stream segments are subjected. Tailwater stream segments or stream segments directly affected by tailwaters from large impoundments present complex water quality management challenges.

History

The U.S. Department of Energy (DOE) initiated a hydropower development program in 1977 to promote small-scale (less than or equal to 30 MW) hydroelectric projects across the country. The Environmental Sciences Division at Oak Ridge National Laboratory studied the environmental effects of hydropower development in 1978 in support of the DOE effort. Since the passage of the National Environmental Policy Act of 1969, regulations and policies regarding environmental interests have been generated by various Government agencies. CE policy demands the preservation of environmental resources (Fischenich et al., in preparation). The potential impact of impoundment upon the quality of resultant tailwaters is well documented (McKinney 1985; Hildebrand et al. 1985). Hildebrand et al.

(1985) summarized analyses of two issues: problems associated with (a) DO in tailwaters below dams and (b) instream flow requirements for fisheries. Also discussed were the technical challenges related to assessment of the environmental effects of multiple-project development in river basins. Water quality, the suite of factors most affecting the integrity of the fish population in the tailwaters, is greatly influenced by hydropower facilities, dam, or flood control structures.

Responding to this challenge, the U.S. Army Corps of Engineers Engineer Manual 1110-2-1605, Chapter 1 (1987), states that "Design of low-head navigation dams should consider measures to prevent environmental degradation . . . Opportunities to add enhancing features should be considered during planning and design. Water quality effects frequently cited for low-head navigation dams are low dissolved oxygen (DO) or nitrogen super-saturation . . . " (U.S. Army Corps of Engineers 1987a)

In 1989, the CE published an Engineer Manual (EM 1110-2-1205) to provide guidance for evaluating how stream channel modifications may affect associated environmental characteristics of the stream system. For example, the environmental considerations of water quality, fluvial geomorphology, ecological resources, and cultural and aesthetic resources were discussed for clearing and snagging, channel excavation, channel paving, bank protection, placement of sediment control structures, and placement of levees for stream channel modification.

The manual still serves as a comprehensive planning document to help in evaluating the environmental impacts of proposed channel modifications. Also, recommendations are presented for the collection of environmental data, data analysis, data interpretation, and decision analysis.

Consideration of water quality issues has resulted in reservoir management plans that relate waste allocation and hydrological modeling to specific water quality criteria (McKinney 1985).

Ideally, probable impacts to aquatic habitats should be considered before project construction. "Balancing power and non-power benefits of hydroelectric developments has become a controversial issue in the relicensing of projects. Multiple project and multiple objective flow management evaluation is at the heart of the controversy. A method for attaining an integrated flow simulation model linked with individual modules . . . [will] . . . enable simultaneous evaluation of the interrelated effects of alternative flow management regimes." (Bizer 1991)

Objectives

The objectives of the overall work unit, of which this report is one product, are presented below (with selected pertinent references):

a. Relate habitat value to channel characteristics based on analysis of existing data or short-term field studies (Nestler, Schneider, and

Latka 1993; Bhowmik and Adams 1990; Klingeman and MacArthur 1990; Stein and Julien 1990).

b. Develop or refine incremental methods for predicting habitat values for different inchannel structures (Nestler 1993; Fajen and Wehnes 1981; Tillman, Dortch, and Bunch 1992; Martin and Dortch 1987).

c. Modify and document instream flow methods for assessment of environmental benefits of channel modifications for tailwaters and flood control channels (Nestler, Schneider, and Latka 1993; Cooper and Knight 1987; Knight 1991; Shields, Cooper, and Knight 1993; Mueller and Liston 1991).

The specific objective of this report is to present the results of a survey of habitat-related channel features and structures in tailwaters, both those in current use and/or planned by the various Federal or State agencies as noted. Where they are available, assessments and the techniques employed to assess the effectiveness of these measures in achieving an improvement of aquatic habitat are also presented.

The effectiveness of a measure is best predicted using mathematical and/or physical models, and by examination of similar measures already in place under conditions similar to the measure(s) being proposed. Models are available that relate flow and other channel characteristics to species diversity and abundance. Methods are being developed to relate habitat value to certain instream structures. Certain programs attempt to forecast, then document and calibrate means of assessing effects of channel modifications on aquatic habitat.

Scope

This report surveys present, past, and planned modifications of tailwaters by the various agencies attempting to improve their suitability as aquatic habitat. Tailwater habitat is profoundly influenced by the operation characteristics of the dam immediately upstream, i.e., frequency, volume, and the position in the pool water column from which water is discharged to the tailwater, besides the factors that may be applicable to flood control channels.

Chapter 2, "Modifications to Enhance Aquatic Habitat," deals with structural and procedural variations used by the various Government agencies, mainly the Corps of Engineers, Tennessee Valley Authority, and the Bureau of Reclamation. Tables are included that show the nature of the modification(s) and the organism(s) they were designed to benefit. Chapter 3, "Assessment of Modification Effects," presents estimates of the efficacy of various measures in various locales and various means by which these estimates were obtained. Chapter 4 summarizes the findings of the survey.

2 Modifications to Enhance Aquatic Habitat

An objective of most improvement projects to enhance aquatic habitat in modified waterways is to design the channel to have natural characteristics at low flows, but with flood control capabilities during extreme events. The hydraulic engineer must incorporate the features of the proposed plan into a final design to accomplish this objective. Specific criteria providing engineering guidance compatible with both flood conveyance and habitat objectives are presently lacking.

Literature Review

The Waterways Experiment Station Online Library Facilities (WOLF) was used for the initial searches regarding tailwater habitat modifications. Among the catalogs queried were the U.S. Army Engineer Waterways Experiment Station (WES) Research Library Collection, the Library of Congress, University of Chicago, Texas A&M University Library, and POLTOX, a pollution/toxicology database. Additionally, much of the relevant literature and personal communication cited originated with the various CE Districts, TVA, Department of Agriculture Agricultural Research Service (ARS), and Department of the Interior BOR.

Other documents including extensive lists of pertinent references were Walburg et al. (1981a), which emphasized tailwater ecology; Dortch, Tillman, and Bunch (1992), which emphasized tailwater quality; Nestler (1993), which emphasized the assessment of impacts on habitats resulting from streamflow aberrations; and Fischenich et al. (in preparation), which emphasized the impacts of instream structures on physical habitat.

Environmental factors affecting the abundance of tailwater fishes were studied (Jacobs et al. 1985) at Barren River Lake, Kentucky. This study demonstrated the effects of both seasonality and project operations on some species. Neves and Angermeier (1990) state that in the upper Tennessee River basin, major impacts on the fish fauna have resulted from dams, introduced species, toxic spills, mining, and agriculture. An important cumulative effect of these impacts is fragmentation of the watershed;

nearly 40 percent of the riverine habitat in major tributaries is either impounded or altered by tailwater discharges.

Nix et al. (1991) and Nix (1986) present field and analytical techniques for studying the mechanisms and chemical transformations occurring in reservoir tailwaters. Their research focuses on the poor water quality associated with deep, anoxic releases from hydropower and nonhydropower reservoirs. Water quality results from the tailwaters of the Little Missouri River (Lake Greeson), Fouche La Fave River (Nimrod Lake), Rough River (Rough River Lake), and Guadalupe River (Canyon Lake) show that the release of anoxic waters high in reduced substances into tailwaters can affect water resources, be hazardous to aquatic life, cause water treatment problems, and affect areas used for recreation. Eventually, the water quality recovers to baseline conditions; however, the chemical and recovery mechanisms of the tailwaters need to be better understood for the practice of effective water quality management. Thus, the goals of the research were to develop an improved understanding of chemical transformations and recovery mechanisms in selected Corps reservoir tailwaters and to provide guidance on sampling and analysis of tailwater quality.

In another study of tailwater habitat, Gore, Nestler, and Layzer (1990) examine habitat conditions on the Caney Fork River downstream of Centerhill Dam, Tennessee, describing peaking hydropower effects with literature surveys and preliminary field work results.

In some cases, habitat degradation can be eliminated, stabilized, or reversed through channel modifications, such as low-cost, low-head weirs for flow modification to create pools, and to aerate the stream. Channel modifications can be used to alter the channel bed to permit more favorable conditions (e.g., substrate) for the growth and vigor of aquatic biota. Modifications can also include structures/methods used for the direct injection of air and oxygen. Often, only minimal and relatively inexpensive changes in dam operation or flood channel design are required. However, since no widely accepted methods exist which quantify aquatic habitat values, it is difficult to weigh costs of enhancements versus habitat benefits.

Martin and Dortch (1987) conclude that "No single method is appropriate for addressing all water quality issues in reservoir tailwaters. Differences in tailwater environments and management issues require that a variety of tools be available for assessing existing or predicting future impacts of reservoir releases."

Sale and Otto (1991) state, "Instream flow requirements are one of the most frequent and most costly environmental issues that must be addressed in developing hydroelectric projects. Existing assessment methods for determining instream flow requirements have been criticized for not including all the biological response mechanisms that regulate fishery resources."

Since this dearth of commonly accepted assessment techniques was recognized, a project was initiated to study the biological responses of fish populations to altered streamflows and to develop improved ways of managing instream flows. The most commonly applied methodology, the Physical Habitat Simulation System (PHABSIM) of the Instream Flow

Incremental Methodology (IFIM), was developed by the U.S. Fish and Wildlife Service (Milhous, Updike, and Schneider 1989). The PHABSIM approach (Loar and Sale 1981; Bovee 1982; Stainaker 1982; Orth 1987; Gore and Nestler 1988; Reiser, Wesche, and Estes 1989), chosen for scrutiny regarding its ability to fill the void, is based on the fact that most species of fish tend to prefer certain combinations of depth, velocity, and cover, and they tend to avoid other combinations. PHABSIM consists of three steps:

a. Describe depth, velocity, and cover available in the river at certain discharges.

b. Develop criteria for each species of fish

c. Combine (*a*) and (*b*) for the discharge values of interest to derive an estimate of the value of the river for each fish species at each discharge (Nestler et al. 1988).

Extensive field data collection and computer models are used to predict changes in habitat in response to discharge.

However, physical habitat-based assessment methods do not represent the biological mechanisms important to population characteristics. Therefore, the predictive capability of habitat indices is questionable, particularly in warmwater and coolwater streams (Morhardt 1986; Orth 1987). The Electric Power Research Institute (EPRI) has focused considerable research effort on the issue, of which the Steam/Hydroelectric Aquatic Population Effects (SHAPE) program is a part. The intent is to provide a more realistic tool for examining tradeoffs between flow regulation and fish resources in the tailwaters (Sale and Otto 1991).

Measures of the various agencies whose responsibility it is to oversee water control structures and their effects on the aquatic habitat downstream currently undertake certain measures to improve tailwater quality. These steps taken to offset the degradation of tailwater quality signified by high concentration of nitrogen species and reduced metals, lowering of DO, streamflow, and temperature, and to achieve the combined goals of desired water levels, temperatures, and solutes in tailwaters include (a) "no action," (b) operational modification, including gate outflow control, selective withdrawal, and active aeration/oxygenation measures, (c) structural modification, (d) streambed modifications, including weirs of various designs, and (e) other actions. Examples of these general methods of improving aquatic habitat in tailwaters follow.

Tables 1 and 2 summarize a selection of specific structures and activities performed by State and Federal agencies with the objective of improving the aquatic habitat in tailwaters. The list is not comprehensive. Some flood channel modifications are also included for illustration. A more detailed narrative of the literature review from which Tables 2 and 3 were derived follows.

Table 1
Control Structures for Enhancing Aquatic Habitat

Agency/Main Structure	Modification	Cost	Completion Date	Benefits
Corps of Engineers				
Omaha District				
Rapid Creek (with SD Game, Fish and Parks and City of Rapid City)	Riprap, wing deflectors, rock ledge pool Boulder clusters, bank cover with a series of pools and riffles.	A	1979	Improve trout habitat
Blue River	Grade control structures, plunge pools, boulders	A	B	Restore reach of river, decrease in width, increase in depth
South Platte River	Rock check dams, rock deflectors Boulder clusters, Biostabilization Revetments	A	B	Decreased warm season temperature Establish adjacent wetlands
Lake Sakakawea	Undergoing study	A	B	Increase DO
Lake Oahe	Localized mixing and selective withdrawal (under study)	A	B	Improve downstream water quality
Kansas City District				
Meramec Park Dam, Missouri	Control weir (physical model)	A	B	Improve DO
Smithville, Hillsdale, and Clinton projects	Selective withdrawal ports Stop logs at the desired elevation	A	B	Improve downsteam water quality
Pomme de Terre project	Metal plates added to trash racks	A	B	Improve downsteam water quality
Harry S. Truman and Stockton projects	Rock weirs	A	B	Fish habitat/reduce entrainment
St. Louis District				
Clarence Cannon Dam	Rock weirs Temperature, DO modification	A	B	Reduce entrainment Improve downsteam water quality
Carlyle Lake	Supplement hydropower releases with spillway releases	A	B	Improve DO
Lake Shelbyville	Supplement hydropower releases with spillway releases	A	B	Reduce H_2S in tailwaters

(Sheet 1 of 4)

Note: A = unknown, B = undetermined.

Table 1 (Continued)

Agency/Main Structure	Modification	Cost	Completion Date	Benefits
Corps of Engineers (Continued)				
Tulsa District				
Eufaula Reservoir Lake Texoma	Modification of release operation	A	B	Improve downstream habitat
Waurika and Lake Wister	Taper shutdown sequence	A	B	Improve downstream habitat
Sacramento District				
Wildcat and San Pablo creeks	Develop riparian vegeration Sedimentation basin Complex cross-section maintenance decided by cross-section monitoring	A	1983	Improve downstream habitat
Vicksburg District				
Narrows Dam on Little Missouri	Three rock weirs/ dam modification Improving bulkheads/trash racks Placing boulders downstream	300K 336K	B	Improve downstream water quality and habitat
Hotophia Creek and others, Yazoo Basin, Mississippi	Snag and debris removal Bank stabilization	304K	B	Restore stream habitat diversity
Harland Creek (with ARS)	Rock faces Paving Transverse groins Graded structures Bendway weirs Willow posts	 101K 75K	B	Restore stream habitat diversity
Lake Greeson	Plates to raise level of withdrawal	A	B	Increase DO and temperature
Table Rock Lake	Undergoing study	A	B	Increase DO
Nashville District				
Martin's Fork Lake	Three selective withdrawal intakes	A	B	Provide temperatures similar to preproject conditions
Wolf Creek Dam	Proposed reregulation dam	A	B	Attenuate hydropower releases

(Sheet 2 of 4)

Table 1 (Continued)				
Agency/Main Structure	**Modification**	**Cost**	**Completion Date**	**Benefits**
		Corps of Engineers (Continued)		
Portland District				
Lost Creek project, Green Peter, Foster, Detroit, Cougar, Big Cliff, and Blue River reservoirs	Studies underway	A	B	Favorable release temperatures
Fall Creek Reservoir	Studies underway	A	B	Increase turbulence in stilling basin
The Dalles Dam on Columbia River Washington/Oregon	Weir modiications Fish ladders (north) Fish ladders (east) Spillway deflector	876K 540K	1986 1985	Improve adult passage Improve adult passage Reduce dissolved gas
Walla Walla District				
Lake Wallula	Operational changes	A	B	Improve smolt passage
Lower Monumental Dam	Spillway deflector	A	B	Decrease dissolved gas
Pittsburgh District				
Marianna Local Flood Channel	Channel modifications	A	1979	Improve downstream habitat
Baltimore District				
Cowanesque Lake	Selective withdrawals	A	1986	Withdraw water of desired temperature
Raystown Lake	Selective withdrawals	A	B	Released desired warm water
Kettle Creek Lake	Selective withdrawals	A	B	Enhance coldwater fishery
Jennings Randolph Lake	Selective withdrawals/flow augmentation	A	B	Improve downstream habitat
Rock Island District				
Lake Red Rock	Discontinue use of tainter gates	A	B	Improve downstream habitat
Mobile District				
Walter F. George Lock and Dam		A	B	Increase turbulence in tailbay Increase DO
				(Sheet 3 of 4)

Table 1 (Concluded)

Agency/Main Structure	Modification	Cost	Completion Date	Benefits
		Tennessee Valley Authority		
	Weirs	50M total budget		
Norris Dam on Clinch	Reregulation weir	800K	1984	Attenuate hydropower water fluctuations
South Holston Dam Holston R/South Fork	Labyrinth weir	1.8M	Dec 91	Increase dissolved oxygen
Chatuge Dam on Hiwassee (Fehring 1991)	Three infuser weirs	1.4M	Nov 92	Increase dissolved oxygen
Blue Ridge Dam/ Toccoa River	Labyrinth weirs	A	B	Increase dissolved oxygen
		Bureau of Reclamation		
Arizona	Concrete-lined water canals Old tires in both flat and upright configurations	30.7K	1988 1989	Increased habitat value for irrigation canals
Yellowtail Afterbay Dam, Montana	Modify discharge from sluice and radial gates	A	B	Improve DO

(Sheet 4 of 4)

Table 2
Habitat Studies Relating to Tailwaters and Local Flood Control Channels by Agency

Location	Organism(s)	Objective
	Corps of Engineers	
Waterways Experiment Station		
Barren River Lake, Ky	Fishes	Understand tailwater ecologic processes
Harland Creek	Fishes/benthos	Enhance aquatic and terrestrial stream corridor habitat
Portland District		
Bonneville Pool and Dam (Bell 1971)	Fishes/ gamebirds	Flows or temperatures of the Columbia River little affected gamebirds at this time (1971). An increase in fish stranding suggested that riverbed configurations should be studied and perhaps altered to minimize this problem. March water levels should be set to provide protection of gamebirds and furbearers during nesting and whelping periods. "Changes during the winter period will have a minimal effect on the environment. For fisheries, rate of downward change is most important; for game birds and animals, the upper water levels during the critical periods (March, April and May) are most important."

(Sheet 1 of 3)

Table 2 (Continued)		
Location	**Organism(s)**	**Objective**
	Corps of Engineers (Continued)	
Nashville District		
Barkley Dam (Sickel 1982)	Mussels	Species diversity/abundance was quantified prior to proposed dredge/fill activities in the tailwaters
Vicksburg District (with Agricultural Research Service, USDA)		
Various Streams, MS	Fishes	Minimize adverse effects of bank protection measures on habitat area Transverse dikes were judged better for habitat than lateral dikes
Hotophia Creek, MS[1]	Fishes	Determine value of scour holes for fishes less than expected for farm ponds
Batupan Bogue Creek, MS (Knight 1991)	Fishes	
Hotophia Creek, MS (berms) (Shields, Cooper, and Knight 1993)	Fishes	Recovery of habitat from incised channels by placing rock spurs and planting woody vegetation (mostly dormant willow posts) Length and numbers of fishes increased tenfold.
Long Creek and North fork of Tillatoba Creek (1985) (Cooper and Knight 1987)	Fishes/benthos	Greater diversity in manufactured pools below grade-control structure Also greater stability. Can increase fish habitat in degraded streams
Harland Creek[2]	Fishes/benthos	Improve channel stability and enhance aquatic and terrestrial stream corridor habitat
Pittsburgh District		
Channel modification (Koryak 1994)	Benthos	Improved fish diversity and productivity compared with original channel bottom
	Bureau of Reclamation	
Concrete lining of water canals (Arizona) (Mueller and Liston 1991)	Fishes/benthos	All species of fish except channel catfish and aquatic organisms (1989) increased in abundance in all configurations although not as great as in earthen sections. Overall, enhanced fish community without effect on canal hydraulics
Yellowtail Afterbay Dam[2]	Fishes	Reduce total gas pressure to tolerable level sedimentation
		(Sheet 2 of 3)

[1] Personal Communication, 5 May 1994, Dave Derrick, Civil Engineer, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
[2] Personal Communication, May 1984, Thomas J. Parks, Natural Resource Specialist, U.S. Department of the Interior Bureau of Reclamation, Billings, MT.

Table 2 (Concluded)		
Location	**Organism(s)**	**Objective**
Wisconsin Department of Natural Resources		
Adams and Marquette counties	Trout	Increase hiding/resting cover
Private		
Irrigation ditch/Spring Creek Montana (Hunter 1991)		
John Day River, Oregon (Hunter 1991)	Trout	Improve fishery, natural reproduction Create cover, stabilize eroding banks, exclude livestock
		(Sheet 3 of 3)

Present Methods

Various Federal and State agencies have been given the responsibility of devising ways to lessen adverse effects of changes in water quality created by water control structures. Speece (1990) discussed measures taken in various dams throughout the United States as examples of attempts to moderate adverse conditions affecting the aquatic habitat in tailwaters and to enhance public benefits. Impoundment of the free-flowing rivers listed altered the discharge patterns, temperature, and DO, changing their downstream aquatic habitats and thus their recreational use potential. Mitigating measures including proper operational procedures have been successful in restoring at least some of the streams' desired attributes. These mitigating measures included no action, gate outflow control, and weir design and placement.

To achieve maximum benefits, TVA has established that tailwaters be managed with certain stated goals (Ruane, Hauser, and Yeager 1990). The goals include devising methods and techniques for predicting and/or measuring the competence of cost-effective modifications that attempt to promote conditions required by aquatic life, particularly fishes. To offset the common effects of impounding a running stream— low DO, undesirable flow regimes, and low temperatures—the principal steps toward determining existing and potential uses of tailwaters follow.

a. Determine opportunity for improving uses of tailwater, including operational modifications.

b. Determine effectiveness of improvement measures in reservoir releases and other methods.

Opportunity for improving tailwater uses is accomplished by the following:

a. *Cooperating with other interested parties.* In the case of TVA, these include State agencies, particularly the State of Tennessee. Within TVA, there are personnel involved with reservoir operations, power operations, engineers involved with aeration and streamflow regulation, recreation specialists, biologists, water quality management personnel, etc.

b. *Selection of uses to be considered.* Balance must be optimized, considering the special characteristics of the particular tailwater.

c. *Preliminary tailwater assessment.* This may include a site survey, acquiring pertinent data on water quality, aquatic life, and existing uses. Also to be considered may be land use in the basins of the tributaries flowing into the tailwater. Minimum desirable flow levels should be determined using mathematical models. Mapping the areas affecting the tailwater characteristics regarding various classes of features, such as aquatic weed growth, location of endangered species, water intakes, etc., contribute to the overall information necessary for informed decision-making.

Effectiveness of improvement measures can be determined by the following:

a. *Preliminary assessment of improvements needed.* These are often related to inflows and other sources of contamination.

b. *Special assessments.* Tailwater DO variability can be crucial in that aquatic life depends on average DO as well as minimum DO.

Walburg et al. (1981a,b) caution that

> Efforts to manage a reservoir tailwater to reflect conditions in an unregulated stream or river are impractical and often impossible because of constraints imposed by the design and operation of the project. Thus, the quantity, quality, and timing of releases create an environment which differs from a natural stream. Understanding the impacts of project releases on the tailwater environment, as well as efforts to minimize detrimental effects and possibly improve downstream conditions, are often determined by overall project design and operation.
>
> Studies are needed to determine the tailwater chemical and physical properties that cause changes in diversity and abundances in the biotic community. Such studies should investigate all parts of the tailwater ecosystem and must include continuous monitoring of major chemical and physical variables and periodic sampling of the tailwater biota... Once sufficient information on the chemical and physical environment of a tailwater is obtained, it should be possible to relate this information to observed changes in the biotic community with appropriate statistical analyses.

(See Nestler and Schneider (1992); Nestler, Schneider, and Hall (1993); Nestler (1993) for implementation of this concept.)

A questionnaire sent to each District in 1988 elicited the responses of 17 CE Districts in 9 CE Divisions regarding their water quality enhancement techniques for 96 projects (Price 1990). Of 28 different techniques mentioned, operational methods were reported to be most successful. For undesirable temperature conditions, selective withdrawal (Cowanesque Lake, Raystown Lake, Kettle Creek Lake in the Baltimore District; Smithville, Hillsdale, Clinton, Pomme de Terre projects in the Kansas City District; Lake Greeson in the Vicksburg District; Martin's Fork Lake in the Nashville District) and operational modifications (Lake Wallula in the Walla Walla District; Lake Red Rock in the Rock Island District; Savage River Dam in the Baltimore District, Lost Creek project, Green Peter, Foster, Detroit, Cougar, Big Cliff, and Blue River reservoirs in the Portland District) were employed in CE projects to deal with unfavorable temperature in the water releases (Price 1990). Success of the different techniques varied from site to site.

To raise DO (or to prevent its decline), operational modification was employed/investigated in projects at Eufaula Reservoir, Waurika Lake, Lake Wister, and Lake Texoma in the Tulsa District; Carlyle Lake and Lake Shelbyville in the St. Louis District; Walter F. George Lock and Dam in the Mobile District; Table Rock Lake in the Little Rock District; and Lake Sakakawea in the Omaha District.

To dilute the concentration of undesirable metals/odor and pH, operational modification and localized mixing were employed in four projects: Fall Creek Reservoir of the Portland District; Gathright Dam of the Norfolk District; J. Percy Priest Reservoir and Old Hickory Lake of the Nashville District. Localized mixing in Priest Reservoir improved the DO and trace metal concentrations, but it did not eliminate the H_2S odor.

The adverse effects of acid mine drainage were diminished in two projects in the Baltimore District—Foster Joseph Sayers Dam and Hammond Lake—with the operational modification of controlling alkaline releases in the reservoir to blend with lower pH water downstream.

Nitrogen species supersaturation was marginally relieved with structural modification of The Dalles, John Day, and Bonneville dams on the Columbia River in the North Pacific Division. Other concerns such as organic sediment accumulation downstream were relieved (with no costs) with selective withdrawal techniques and flow augmentation of the Jennings Randolph Lake in the Baltimore District and Lake Oahe in the Omaha District. Solving a downstream ice formation problem with localized mixing and selective withdrawal was investigated at Lake Oahe of the Missouri Division.

Table 3 summarizes the results of Price's survey of CE Districts and Divisions' efforts to improve the quality of the tailwater.

The principal kinds of modifications practiced by other agencies as well as the CE may be categorized as follows: no action, operational modification, structural modification, streambed modification, and others. These categories are listed separately, with examples, in the paragraphs following.

No action

The flow into Hell's Canyon on the Snake River, Idaho (BOR), is controlled by upstream dam discharge. Since this stretch of the Snake River

Table 3
Water Quality Enhancement Techniques of Corps of Engineers Operations (from Price 1990)

Problem	Method	CE District	Location
Undesirable temperature conditions	Selective withdrawal	Baltimore	Cowanesque Lake Raystown Lake Kettle Creek Lake
		Kansas City	Smithville Hillsdale Clinton Pomme de Terre projects
		Vicksburg	Lake Greeson
		Nashville	Martin's Fork Lake
	Operational modification	Walla Walla	Lake Wallula
		Rock Island	Lake Red Rock
		Baltimore	Savage River Dam
		Portland	Green Peter, Foster, Detroit, Cougar, Big Cliff, and Blue River reservoirs
		Tulsa	Eufaula Reservoir Waurika Lake Lake Wister Lake Texoma
		St. Louis	Carlyle Lake Lake Shelbyville
		Mobile	Walter F. George Lock and Dam
		Little Rock	Table Rock Lake
		Omaha	Lake Sakakawea
Undesirable metals, odor, and pH	Operational modification and/or localized mixing	Portland	Fall Creek Reservoir
		Norfolk	Garthright Dam
		Nashville	J. Percy Priest Reservoir Old Hickory Lake
Acid mine damage	Operational modification by controlling alkaline releases	Baltimore	Foster Joseph Sayers Dam Hammond Lake
Nitrogen species supersaturation	Structural modification	North Pacific	The Dalles Dam John Day Dam Bonneville Dam
Organic sediment accumulation downstream	Selective withdrawal with flow augmentation	Baltimore	Jennings Randolph Lake
Ice formation downstream	Localized mixing and selective withdrawal	Omaha	Lake Oahe

was deemed valuable as a salmon-spawning area, BOR's previous plans for a 600-ft dam project was aborted so that the unique habitat could be maintained. Other examples exist in which planned projects were canceled or severely curtailed because habitat critical to an endangered or threatened organism was involved.

Operational modification

Operational modification has been used with varying success to control discharge, to control water temperature, to raise DO, to dilute the concentration of trace metals, and to ameliorate the effects of acid mine drainage. Ocoee River in Tennessee and Georgia (TVA) had its generating schedule modified to provide for whitewater rafting, resulting in a net loss of hydropower generation. The loss of income from the modification was, however, offset by charging a user fee to the rafters.

TVA completed the Upper Bear Creek Reservoir in January 1980. The dam has a self-regulating overflow spillway with a crest elevation of 243.5 m (800 ft) median sea level (msl). Recreational floating in the tailwater requires 7.1 cms (250 cfs) during summer weekends. These releases are supplied from an intake tower that has two gates located at elevations 221.7 m (727 ft) and 235.4 m (772 ft) msl, respectively. The lake is 21 m (69 ft) deep at the dam with a volume of about 42,000,000 m^3 (34,000 acre-feet) and an average annual outflow of 5.6 cms (198 cfs).

Thermal stratification of Upper Bear Creek Reservoir begins in May and persists until November. The DO declined to less than 1 mg/ℓ below the thermocline in early summer, allowing releases of reduced iron, manganese, and sulfide compounds. A multiple-level intake structure for water supply had experienced problems with high metal levels from the hypolimnion and warm temperature and chlorine residuals from the surface. To relieve these problems, an air bubble diffuser was installed to provide mixing and aeration of the reservoir's hypolimnion.

Table Rock Dam on the White River, Missouri (CE), forms a relatively deep impoundment that stratifies during the summer. The tailwater was a shallow-pooled river prior to the impoundment and supported a resort industry based on water-skiing. After construction of the dam, discharge of cooler water had an adverse impact on water-skiing, but allowed for the growth of shrimp, leading to a robust trout fishery. Subsequent low DO levels, however, adversely affected the trout catch. Discharge operation of Table Rock was then modified to maintain a more favorable DO.

Niagara Falls, New York (CE), receives its water from Lake Erie. Hydroelectric generation through two 45-ft diam[1] tunnels is scheduled so that water is available for prime viewing time by tourists.

Richard B. Russell Dam in Georgia (CE) provides a coolwater fishery due to the large, stratified reservoir in an otherwise warmwater Savannah River.

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[1] A table of factors for converting non-SI of measurement to SI units is presented on page viii.

The CE ensures a minimum required DO level of 6 mg/ℓ by injecting pure oxygen in fine bubble diffusers submerged 140 ft on the reservoir bottom (Speece 1990).

Releases from J. Percy Priest Reservoir in the Nashville District (CE) were improved by localized mixing to control trace metals and H_2S and to obtain DO objectives. Higher quality epilimnetic water was mixed with lower quality hypolimnetic water in front of hydropower intakes, thereby improving the quality of the released water (Price 1990).

Although most released water temperature concerns have to do with cold releases from the deeper hypolimnion when a pool is stratified, some projects suffer from cold releases during low-flow or nongeneration periods. Selective withdrawal techniques, which include numerical models of system capacity and design to meet project requirements, are implemented to release warmer water. To control the release temperature for fisheries downstream, these techniques are applied at the CE impoundments Cowanesque Lake, Raystown Lake, and Kettle Creek Lake of the Baltimore District; the Smithville, Hillsdale, Clinton, and Pomme de Terre Projects of the Kansas City District; Lake Greeson of the Vicksburg District; and Martin's Fork Lake in Nashville District (Price 1990).

Broome (1991) proposed the following concept as a possible variation of the technique of selective withdrawal as a means of achieving the water quality desired for habitat: "Deep intakes at hydroelectric dams in southern states withdraw water that is oxygen deficient during summer months when reservoirs become stratified. The *"Gloryhole"* approach to solving this problem uses a funnel(s) of stiffened geotextile fabric suspended from a buoyant ring(s) to withdraw water from surface strata that are usually much richer in oxygen content. The bottom of the funnel(s) is (are) fastened around the intake(s) to the hydroelectric plant, thus replacing oxygen deficient bottom water with oxygen rich surface." An application of this concept is proposed for the hydroelectric plant at the U.S. Army CE Richard B. Russell Dam in Georgia. The system consists of (a) a circular floating platform with access bridge and mooring lines, (b) a conical funnel of stiffened fabric suspended from the perimeter of the floating platform, and (c) a connection between the lower end of the funnel and the perimeter of the intake to the hydroplant. The estimated cost of the proposed system to Russell Dam is one million dollars.

The Coosa River below Jordan Dam, Alabama, supports a multispecies, warmwater tailwater fishery. Maintaining sufficient flow to protect this fishery while simultaneously allowing substantial portions of water to be diverted from Jordan Lake through a new hydroelectric facility, from which the water is returned via a canal to the Coosa River 21 km below Jordan Dam, thus bypassing the Jordan Dam tailwater, has become a principal concern. Water temperature and streamflow were the most important independent variables during early and late summer. The two most important variables identified for the stilling basin during these two seasons were Secchi disc visibility and barometric pressure. Angler effort was positively correlated with wind velocity during early summer and with minutes of sunshine during late summer. Angler effort was negatively related to streamflow. A minimal-flow regime appears to be acceptable for this type of tailwater fishery during the summer as long as discharges are adequate to maintain stream productivity (Jackson and Davies 1988).

Structural modification

The overall TVA program current in 1984 (TVA 1984) consisted of developing and implementing cost-effective ways for enhancing water releases from TVA reservoirs where DO and flows adversely impact downstream uses, including economic development and recreation. Also considered was mitigation of power losses resulting from aeration measures. Hub baffles replacing earlier designs reduced power losses at Norris Dam from almost 500K per year to 60-70K per year because the newer baffles are more streamlined and because they can be quickly installed and removed when they are not needed. This design is unfortunately not easily translated for use in other dams. Alternate approaches such as compressed air were successful in eight projects.

Structural modification has also been marginally successful in reducing N supersaturation in three CE Columbia River projects in which it has been tried. In each case, the trajectory entrains large quantities of air before submerging in the tailwater, forcing high quantities of N into solution, which increase with increasing discharge. By deflecting the release from entering the tailwater directly, entrained air is reduced significantly. Although this technique has been studied extensively, its success in reducing dissolved N is evaluated as limited.

Low DO in discharges of hydroelectric plants is being addressed with the autoventing turbine, with TVA coordinating research performed in cooperation with the U. S. Army Corps of Engineers, the U. S. Bureau of Reclamation, and the Iowa Institute of Hydraulic Research (Waldrop 1991).

McNary Dam on the Columbia River, operated by the Corps of Engineers, is the first dam downstream from the confluence of the Columbia and Snake rivers, thereby influencing the migrations of both river systems. To offset the mortality (estimated at 11 percent) of yearling chinook salmon, a juvenile fish bypass system was installed in 1981. It includes a collection facility for salmonids to be transported to a release site below Bonneville Dam. The standard-length submersible traveling screens (STS) were designed and installed to divert juvenile salmonids away from the turbine intakes into gatewells for collection (McComas et al. 1993). In 1992, the six turbine units at Lower Monumental Dam were fully equipped with STSs, and research was conducted during the spring juvenile salmonid outmigration to determine the fish guidance efficiency and orifice pass efficiency (Gessel et al. 1993)

Streambed modification

Streambed modification has been studied by the CE, often in conjunction with other Federal or State agencies. For example, the CE cooperated with the U.S. Department of Agriculture ARS to improve the aquatic habitat potential in flood control channels in the Yazoo basin (Cooper and Knight 1987; Knight 1991; Shields, Cooper, and Knight 1993). Hunter (1991) and Fischenich (1994) describe several case studies of trout habitat enhancement on "natural" streams, featuring stream habitat improvements effected by the CE working with State and local agencies. Rapid Creek, South Dakota, has been extensively channelized for flood control, road and railroad construction, and urban development, resulting in the original stream length in the Rapid City urban area being reduced from 48 to 14 km (Glover 1979). Rehabilitation of Rapid Creek consisted principally of the use of five features—riprap, wing deflectors, rock ledge pools, boulder clusters, and bankcovers. Other forms of streambed modification to enhance aquatic habitat have been attempted by the BOR (Mueller and Liston 1991), where old tires were used in concrete-lined water supply canals.

Standard trapezoidal flood control channels are known to have limited environmental quality. Flood control channels are part of a complex ecosystem that is affected and controlled by numerous interrelated variables. Any modification to the physical character of the stream will affect the other variables and impact water quality, aquatic habitat, terrestrial habitat, wetlands, and aesthetics. The degree of the impact is highly variable and both spatially and temporally dependent (Fischenich 1991).

Shields (1991) presented design criteria for sills, deflectors, and randomly placed rock in open channels. He indicated that a broad-crested sill that is submerged most of the time may act as a riffle. Notching the sill will concentrate the flow into a low-flow channel to provide greater depths and maintain scour holes. The use of a central gap sill structure usually requires that downstream banks be protected from erosion with riprap for a distance equal to one to three channel widths. Sills should be well keyed into the bed a minimum depth of twice the height of the sill above the channel invert.

Deflectors are structures that protrude from one bank but do not extend the width of the channel. They can be angled upstream, downstream, or placed perpendicular to the bank. In plan, deflectors may be simple jetties, or triangular in shape. Deflectors in series are usually constructed or placed on alternate banks to produce a meandering thalweg. They should be keyed into the bank and bed in a manner similar to sills.

Instream structures should be sized to produce the desired aquatic habitat at normal and low flows with little effect on the channel flow capacity. Structures should be low enough so that their effects on the water surface profile will be almost completely drowned out at near-capacity discharges. The maximum height of a sill above the channel invert should be no more than one-third the bankfull water depth, and the lowest point on the sill crest (such as the invert of a notch) should be at the upstream channel invert elevation. Structures should be spaced to avoid large areas of uniform conditions. A minimum spacing of three pool lengths between structures and a maximum pool length of five channel widths are recommended. Deflectors should extend one-third the stream width into the channel. Bank protection should be used opposite a deflector. Random boulders should be sized to withstand the maximum velocity but should be no larger in their greatest dimension than one-fifth of the channel width at normal flow. The long dimension of the rock should be placed normal to the current and project slightly above the water surface at normal flow.

Stein and Julien (1990) report a study of sediment concentrations below small headcuts.[1] "This study is designed to determine erosion rates downstream from a small headcut. In all cases, sediment concentration from the scour hole decreases logarithmically with time. All runs for a given bed material are approximated by a single curve after using the normalizing parameter $T^* = T\ U_0 / Y_0$," U being velocity and Y being thickness of the jet at tailwater impingement.

Klingeman and MacArthur (1990) include coarser grained gravel in the bed material considered. "Gravel-bed rivers experience dynamic conditions of flow and sediment transport. Long periods of bed stability are interrupted by shorter periods of bed mobility when major changes and corresponding adjustments occur. Aquatic habitats in alluvial channels are affected by, and make spatial and temporal adjustments to, hydraulic conditions and sediment transport processes. Mobilization of bed material affects benthic habitat and therefore, aquatic communities. Interrelations of habitat characteristics, sediment transport, and bed-material movement are described for gravel-bed rivers."

Recognition of the environmental concerns related to channel modification for flood control has led to the development of channel designs that facilitate "natural" channel conditions during normal flow but increase floodflow conveyance. Single bank modification, compound channels, high- and low-flow channels are examples of features used to accomplish these objectives.

Nunnally and Shields (1985) define a low-flow channel as a subchannel constructed inside a larger flood control channel to concentrate flow during low- or moderate-flow conditions. Not all low-flow channels produce significant environmental benefits. For example, a V-bottom cross section provides required conveyance but little aesthetic, water quality, or fish habitat value. On the other hand, a meandering low-flow channel carrying permanent flow can enhance aquatic habitat, water quality, and aesthetics.

According to Bhowmik and Adams (1990) "...aquatic habitats and their propagation are intimately related to the characteristics of flow within the main river and amount of sediment and organic matter transported by the river. Floods distribute organic matter to the floodplains; large-scale sandbar movement can destroy substrate habitats, and large rivers have many retention and detention devices that are important for the biological diversity of the river, while their hydraulic characteristics are essential in maintaining localized habitats."

Klingeman and MacArthur (1990) predict aquatic habitat characteristics. "Sediment transport and bed-material movement can have significant impacts on the formation and alteration of aquatic habitat. Lateral variability in channel conditions contribute importantly to habitat diversity. The influence of antecedent events is significant, as channels try to adjust to a dynamic equilibrium whenever bed-material movement occurs. Major

[1] A headcut is an abrupt break in an ephemeral channel bed slope. Headcuts incised in rills usually occur in cohesive soil and a plunge pool just downstream from a near vertical face.

floods are particularly critical in moving very large roughness elements and in establishing the major features characterizing habitats. Smaller floods contribute to lesser modifications in habitat appearance and quality but may provide a flushing mechanism to remove fine sediment and detritus."

Sediment load and flash flooding exacerbated by man-made structures and activities are also considered in aquatic habitat enhancement.

Detention devices effectively increase the travel time of water sediment and energy fluxes through the system. Ripples and dunes on the bed trap food for benthos and fish and increase the temporal stability of stream ecosystems by trapping pulse input of nutrients and storing for consumption at later times.

Retention devices may be on the scale of the bed-material grains' size, the bed-form height, or the water depth, stream width, or stream segment. Anthropogenic features such as dikes, wing and closing dams, roadway embankments, and dams also function as retention devices. Structural approaches can, however, inhibit a stream from restoring itself. Often, streams can change location dramatically as a stream moves toward dynamic equilibrium, but channel structures can lock the channel in place, limiting the stream's flexibility (Hunter 1991).

Weirs. A weir is generally described as a dam designed to divert the streamflow and to raise the water level of the stream. Weirs are generally considered to be low sills designed to be submerged most of the time. Gabion weirs (mesh structures filled with another material type, e.g., gravel or rocks) can be classified into three types based on their downstream face: vertical, sloped, and stepped. Hydraulic design of gabion weirs must consider the crest to maintain the maximum discharge, design of the stilling pool for energy dissipation and control of scour, and control of seepage under and around the weir.

Weirs are built across channels for purposes including soil erosion control, flood damage reduction, sediment trapping, flow measurement, groundwater recharge, and upstream water level elevation. Upstream water level elevation may form pools, support pumping station intakes, and produce a channel reach suitable for navigation. By flattening the local stream gradient, channel scour may be reduced and bed deposition may be increased, protecting upstream structures from scour and banks from erosion. They can also be installed to encourage fish spawning by trapping gravel and by creating scour holes.

Weirs have long been used to modify fish habitat by altering water depths and velocities and by inducing local bed scour and sediment deposition. Klingeman, Kehe, and Owusu (1984), sponsored by the Water Resources Research Institute of Oregon State University, attempted to determine the effect of V-shaped gabion weirs on the streamflow and bed scour patterns and the influence of weir apex angle on channel scour and deposition characteristics using laboratory experiment followed by field observations. A desirable scour hole for fish habitat modification is considered to be one that is deep and large and provides enough room for fish rearing, while maintaining favorable temperatures during periods of low flow. Also, its location must not pose a threat to the weir itself or the streambanks.

Klingeman, Kehe, and Owusu tested weir apex angles to determine the size and nature of scour holes thus formed, since this knowledge is directly applicable to the creation of fish habitat. However, bank erosion under these conditions was also observed to determine if bank protection measures would be needed. All weir angles produced about the same scour width except when a straight weir condition was examined where bank protection such as revetments might be prudent. Also, the straight weir gave the minimum scour length; the smallest angle tested (30 deg) gave the maximum scour length.

The scour patterns observed in the laboratory were reproduced in the field investigations, with the deposition of sediment in the middle of the channel when two or more V-shaped weirs point downstream. Moreover, gravel was easily trapped behind the weirs. Diagonal weirs also trapped gravel, causing scour and increasing bar deposits downstream. The biggest scour hole development can be expected to occur for a weir apex angle range between 90 and 120 deg, producing maximum scour depth and volume. Weirs in herringbone layouts, W-shaped weirs, and F-shaped groins were tested for fish habitat enhancement purposes in Oregon streams.

Weir design and placement have been examined with mathematical and physical models by TVA (1983, 1984), the BOR at least since the 1960s, and the CE before the 1980s(U.S. Department of the Interior BOR 1963, 1965, 1990; U.S. Army Corps of Engineers 1970, 1979a,b, 1983, 1985, 1987a,b,c, 1989, 1992). (The U.S. Army Corps of Engineers (1977) proposed the use of a weir to control ice-jam flooding from the Israel River to the town of Lancaster, NH. A gabion structure was selected as best for the purpose and having negligible environmental impact. Fishes were predicted to be able to negotiate the gabions during both moderate to high flows as well as during low flows. The weir structure itself was expected to permit colonization of invertebrates and algae, thereby increasing species diversity and abundance.)

To date, more success in practical water quality improvement from an aquatic life perspective has been gained by installing weirs of various designs below the primary dam than with most other measures. Weirs have been investigated for many years, since they can be designed to divert or otherwise modify water flow and thus control movement of fishes. Generally, in the context of improved water quality or improved aquatic habitat, weirs are effective because they allow water to overtop them, promoting aeration and cooling and providing for the water that has moved around and through the generating plant to remain longer between the dam and the weir. This practice can ensure the minimum flows necessary for the vigor of the aquatic biota.

This increased aeration, lowering of water temperature, and prolonging the time the water remains in the channel usually result in more favorable fish habitat (TVA 1984; Hauser et al. 1992a,b; Hauser 1992; Hauser and Brock 1994; U.S. Army Corps of Engineers 1992; Bohan 1970; Bohac 1989; Leutheusser and Birk 1991).

Tennessee Valley Authority. TVA designed a mathematical model, followed by a physical model, to examine various rock or gabion weir cross sections (Loiseau and Harshbarger 1983; Hauser and McKinnon 1983). Both the mathematical and the physical models were constructed to investigate discharge coefficients for flow over or through the weir and navigation conditions near the weir.

Two acceptable weir cross sections were developed for the proposed site. The reregulation weir of the "best" design was to be placed in the Clinch River downstream from Norris Dam (Tennessee) to capture water from the peaking release of the hydropower dam to maintain a minimum flow during periods when the turbines were idle. Hydraulic effects of the weirs were simulated using computers, varying sites and weir heights. Also considered was the navigation of small boats during weir overflow.

Generally, the performance of all of the configurations was very sensitive to tailwater elevation. A change of as little as 6 in. was enough to alter the size and shape of the hydraulic jump and the standing waves. A 30-ft cross-section weir with rock gabions performed best. The upstream vertical dimension was 5 ft, with four 6-in. drops to a height of 3 ft. A shorter 21-ft cross-section weir was tested and performed almost as well as the 30-ft weir, except that it was more sensitive to tailwater elevations. Physical models were then used to confirm the mathematical predictions and to observe flow for navigation requirements.

A mathematical model of unsteady flow was used to evaluate a rock weir below Norris Dam. A 5-ft weir with float-actuated controls on 20 of the 54 discharge pipes approximately 2 miles below Norris Dam was recommended to provide 12 hr of the 200-cfs minimum flow. However, downstream flow and temperature impacts were not addressed with this model (Hauser and McKinnon 1983).

According to Harshberger (1985), field evaluation gave opportunities to "fine-tune" the weir design examined in earlier model studies.

> Field tests to evaluate the hydraulic characteristics of the Clinch River weir were conducted in the spring and summer of 1984. Overall flow patterns at the weir were satisfactory and verified conditions predicted from model studies.
>
> As constructed, flows through the weir were not satisfactory. There was too much leakage and the flow decreased too rapidly following turbine shutoff at Norris Dam. After leakage repairs and plugging of some of the pipes through the weir, flow conditions were satisfactory. In the modified condition, an average flow estimated at 180 cfs is maintained for a period of 12 hours following turbine shutoff at Norris Dam. The minimum flow measured was 165 cfs over a 4-hour span during this 12-hour period. Estimated leakage could increase this minimum another 5 to 10 cfs.

The weir on the Clinch River as described by Shane (1985) is constructed of galvanized steel gabion baskets filled with 4- to 8-in. washed limestone rock. It is 5 ft high, 21 ft wide, 423 ft long with fifty-four 12-in.-diam steel pipes passing through it for discharge control. The overall objective is to improve the quality of the fishery through increased numbers of trout harvested, attracting a large number of fishermen to the site. To this goal, the hydraulic, aeration, and habitat gains resulting from the installation of the reregulation weir were quantified.

"TVA is in the initial phases of a project to provide minimum flows in the South Fork Holston River below Holston Dam....to enhance the existing fishery (rainbow trout) and help ensure the water supply availability for the city of Bristol, Tennessee." Alternatives considered, some based on TVA's previous successes with streamflow regulation, included a reregulating weir as at Norris Dam (TVA 1983), pulsing existing generating units as at Cherokee and Douglas projects, and a small (80-cfs continuous release) generating unit such as was installed at Tims Ford Dam. The reregulating weir was chosen because it would provide positive net benefits and a Benefit-Cost ratio greater than 1. The previous success of the Norris weir and its visibility to the public were significant considerations in choosing the weir alternative. Designing aerating properties into the weir rather than having separate aeration facilities at the dam was deemed more economical, although the required weir design would be a costlier labyrinth design (Hauser 1991) with higher initial construction costs.

Hauser et al. (1992a) furnished the design steps for the TVA weirs constructed on the Clinch and South Holston rivers: (a) timber-crib weirs for minimum flows and (b) labyrinth weirs for minimum flows and aeration. Designs include measures whereby water can be maintained in a channel that would otherwise be dry when the dam was not generating.

Advantages of these designs are hydraulic and aeration performance, weir safety, and ease of construction. However, since timber cribs are attractive to the fishing public, they can become an "attractive nuisance," in that the fishermen can put themselves at considerable risk by walking out onto the structure to gain a better vantage point from which to angle. In the event of a mishap, the weir builder may be exposed to litigation. The labyrinth weir, on the other hand, cannot be used as a fishing pier and is not navigable, but construction of the required crest length to aerate high-flow applications safely costs considerably more than for timber-crib weirs.

Section views of the timber-crib weir and a perspective view of the three-bay labyrinth weir are shown in Hauser et al. (1992a,b). Target minimum flows were selected in a tradeoff evaluation that considered (a) visual observation, (b) incremental (modeled) physical changes with increased flow, (c) professional judgment of aquatic benefits, balanced against assessment of impacts to (a) recreation, (b) upstream reservoir pools, and (c) annual power production.

Minimum flow targets ranged from 50 to 100 percent of the unregulated 7-day 10-year low flow, requiring that the weir store enough water to achieve desired drain times necessary for the maintenance of a minimum target flow.

Site-specific physical modeling is recommended prior to construction. (Hauser (1992) also furnished a summary of performance testing of South Holston labyrinth weir regarding hydraulics and aeration.) Weir construction is financed as part of a TVA 50M[1] capital budget to improve DO levels and minimum flow characteristics.

TVA began building an infuser weir downstream of Chatuge Dam on the Hiwassee River in 1994. More compact than the labyrinth design, it is still expected to aerate as well, but with less construction cost. A third weir of labyrinth design was being considered to be placed below the Blue Ridge Dam on the Toccoa River. If the design had been accepted, it was scheduled for completion in 1994.

TVA tested a novel idea at a small embayment at Holston River Mile 55 that purported to provide an inexpensive alternative to aeration of an entire reservoir for maintaining appropriate temperature and DO for certain desirable fish species (Bohac 1989). The temperature of the epilimnion of the Cherokee Reservoir in northeastern Tennessee exceeds the optimum temperature range for striped bass, while the hypolimnion, which might contain cool water, has insufficient DO. Popular refuge areas used by the fishes are spring-fed embayments, with waters typically high in DO. These areas can crowd, however, allowing rapid spread of disease among the fishes. Artificial reaeration could solve the DO problem, but relying on artificial reaeration alone would be prohibitively expensive. Hence, an artificial refuge approach was selected.

> It was possible to construct a fabric dam underwater with a bottom seal sufficient to maintain a temperature gradient between an embayment and the main body of the reservoir. The maximum observed temperature gradient over the three summers of operation was about 14 °F. Aeration in the coolwater pool behind the dam was successful in attracting some fish that prefer cool water. However, an anoxic layer at the top of the barrier and temperatures below optimum in the coldwater pool may have discouraged striped bass from inhabiting the refuge until late summer, rather than in early summer as desired. Modifications should be made to the aeration system to provide oxygen in warmer water above the barrier. However, in its existing condition, the refuge might be suitable for young striped bass which do best in water 68 °F or cooler in the first month of life.
>
> Submerged fabric dams might have application to provide more desirable aquatic conditions in portions of large reservoirs at much less cost than manipulating the whole reservoir to provide the desired environmental conditions. Such dams could also be used to provide different aquatic conditions for different species in the same reservoir. Such dams on a larger scale might also be used to store cold water for release from hydropower projects later in the summer. An underwater dam located near a turbine intake might also be used to change the withdrawal zone of the turbine to save cold water, permitting cool late-summer releases. Cooling the releases could help in reducing stress in salmon during their spawning runs.

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[1] M = one million U.S. dollars.

Corps of Engineers. Rudimentary design guidelines for simple structures including sills, current deflectors, and boulders, focused on coarse bed material streams, were reported by Shields, Cooper, and Knight (1993) for rehabilitation of aquatic habitats in unstable streams.

Cooper and Knight (1987) describe man-made pools below grade-control structures similar to natural scour holes in terms of the total number and weight of fish as well as weight per volume. However, examination of individual components and several commonly used indices of fisheries quality revealed greater potential for man-made pools. Greater diversity and stability of reproductive habitat were evident in the grade-control structure pools. Though with less potential for a sustained fishery than that for a farm pond, man-made pools can increase fish habitat in degraded streams.

The test areas for the field study begun in the summer of 1985 were located along Long Creek and North Fork of Tillatoba Creek in north central Mississippi (Yazoo Basin). Total volumes of 1,074 m^3 for natural pools and 1,329 m^3 for man-made pools were considered. Surface acreage of pools ranged from 13 to 950 m^2 with depths ranging from <1 to 3 m.

Limited design criteria for the enhancement of some low-flow environmental features were presented in Engineer Manual EM 1110-2-1205 (U.S. Army Corps of Engineers 1989). For example, the incorporation of pools and riffles into design of the low-flow channel was encouraged to provide a variety of water depths and flow conditions for maintaining biologic diversity and vigor. Pools and riffles tend to be spaced with pool-to-pool distances that fluctuate about a mean value of five to seven channel widths for most typical streams. On meandering streams, pools are located in bends, and riffles are found in straight reaches. Pools and riffles may be placed in subchannels, low-flow channels, or larger channels with stable beds.

The spacing of pools and riffles in paved channels is not considered to be critical. However, the manual recommended that the design low-flow channel width be sized for the 1-year return interval flow. Pools should alternate from side to side within the channel, and sediment transport conditions of the channel should mimic preproject conditions. Although the size and shape of the pools are not as critical as spacing from a hydraulic standpoint, biologic guidance should be sought to conform to site-specific requirements. Pools should have a minimum low-water depth of 30 cm, and riffles should not project more than 30 to 50 cm above the mean channel invert. Generally, individual pools should not be longer than three channel widths or shorter than one. Riffle lengths should be one-half to two-thirds that of pools, and channel width in riffle areas should be 10 to 15 percent wider than in pool areas.

Shields (1991) developed environmental guidance for flood control projects that involve modification of natural stream channels. He indicated that channel improvements yielded shorter, smoother, more uniform channels with larger cross-sectional area and less natural vegetation than found in natural channels. These "improvements" may enhance conveyance but are not necessarily environmentally advantageous. Channel straightening should be minimized due to its impacts on ecological and aesthetic resources. Shields advocated the use of low-flow channels to lessen the adverse impacts of channelization. Riffles, pools, and water control structures should be considered when possible.

Environmental features to be considered in channel modification should include selective clearing and snagging, channel enlargement, single-bank modification, floodways, water level control, preservation of severed meanders, placement of sediment traps, vegetation, installation of sills and deflectors, and placement of random rocks. Channel form specifics must address pool-riffle complex, habitat diversity, riparian vegetation, and substrate.

Knight (1991) describes the streams of the hills of northern Mississippi as having unstable beds of clay or shifting sand, with occasional scour holes supporting larger fishes. Bank protection can adversely affect fish populations, but those measures that promote the creation of scour holes nonetheless provide refuge in a habitat-limited environment and thus benefit fish. A 3-year study of the Demonstration Erosion Control (DEC) Project in the Yazoo Basin evaluated streambank protection techniques for impact on catch per unit of effort, total catch, total numbers, and species diversity of fishes of Batupan Bogue Creek near Grenada, MS.

Shields, Cooper, and Knight (1993) describe measures used in the DEC effort in local flood control channels. The recovery of severely degraded aquatic habitats typical of incised stream channels may have accelerated recovery through deposition of sandy berms by placing rock spurs in the channel and by planting woody vegetation on the berms.

The Bendway Weir in a navigable river is loosely defined as a rock structure built of graded stone located in the navigation channel of a bend and angled from 10 to 30 deg upstream of a line drawn perpendicular to the bank line at the bank end to the weir. It must be of sufficient size to intercept enough flow that the following conditions (hydraulic improvements) are accomplished:

a. Wider navigation channel.

b. Deposition at the toe of the revetment on the outside of the bend.

c. Relocation of the channel thalweg to a position along a line connecting the river ends of the weir.

d. Surface currents do not concentrate on the outer bank of the bend.

e. More uniform flow velocities across bend cross sections.

f. Improved navigation channel in the crossing downstream of the bend.

g. Improved alignment of the navigation channel throughout bend and downstream crossing.

The CE Vicksburg District and WES tested systems of Bendway Weirs and other bank stabilization methods for application on a reach of Harland Creek, part of the Black River watershed contained in the Yazoo River basin. The reach is approximately 12,000 ft long and averages 75 to 150 ft in width from top bank to top bank.[1] The original plan was to design, construct, and monitor one set on Bendway weirs in one unrevetted bend in a small river. The scope expanded to include a stream reach with 14 distinct bends. It now includes willow post planting where applicable, used as either stand-alone bank protection or in combination with Bendway Weirs. Further, where conditions warrant, traditional longitudinal stone toe dikes (with tiebacks) would supplement the Bendway Weir and willow post bank protection structures.

The DEC project is not purely research; rather, each set of bank protection was specifically designed for the particular reach in which it was employed. Further, the design was such that the bank protection measures would not require extensive maintenance to prevent failure.

A section of Harland Creek in Holmes County, Mississippi, was chosen because (a) it is fairly stable, not actively meandering; (b) it is not deeply incised; (c) it has a number of bends with actively eroding banks; (d) its size is suitable for the purpose; (e) field trips from Vicksburg can be completed in 1 working day; and (f) it has appropriate flow characteristics to test the Bendway Weir and willow post bank protection structures.

Habitat improvement will result in the following desirable features: (a) occasional deep pools; (b) stable scour holes at least twice as deep as the average stream depth; (c) stable habitat; (d) both pool and riffle habitat; (e) solid substrate for invertebrates; (f) wide stone size gradation to benefit a variety of benthos; (g) canopy cover for shade and source of detritus and insects into stream; (h) woody debris; (i) stone dike providing greater diversity of habitat; and (j) low-water channel meandering in weir field providing best habitat potential.

Over 400M is spent each year in an attempt to stabilize banks (Stroupe 1994). One innovative method, costing about half as much as current methods, is using a combination of weirs and willow posts as part of a project on Harland Creek in the Yazoo Basin. Several Federal agencies in addition to the CE are participating in the effort. In addition to offering traditional bank stabilization, there is also promise of aquatic habitat enhancement. The Harland Creek project includes 54 bendway weirs on 14 bends on 12,000 ft of streambank. Planting of over 9,000 willow posts is planned. The technology will take a few years to reach its full effectiveness, but any stream system with meandering streams, flash flood flows, and erodible banks would be good candidates for the implementation of this rather inexpensive technology. A wide variety of better habitat conditions will be provided compared with existing conditions or to other standard bank stabilization measures.

Harry S. Truman Dam, one of the most highly developed recreational lakes in the entire Midwest, is located in west-central Missouri on the Osage River and in the headwaters of the well-known Lake of the Ozarks. Construction and operation of the Harry S. Truman project has created the potential for directly affecting the water quality of the Lake of the Ozarks.

[1] Personal Communication, 1994, D. Derrick and D. Abraham, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Linder (1982) described the features of the Harry S. Truman project, the development of a water quality monitoring program for the project, and operating experience since closure of the embankment in July 1977. Major fish kills have occurred as a result of supersaturation downstream of Harry S. Truman Dam, as well as brief periods of depressed DO in the tailwater area. In both cases, structural modifications and adjustments in project operations have provided solutions to significantly reduce downstream water quality problems.

U.S. Army Corps of Engineers (1979a,b) demonstrated the need for a skimming weir in the approach channel of Harry S. Truman Dam to maintain satisfactory water temperatures and DO in the immediate downstream reach of the Osage River during summer generation periods. The water quality was defined with respect to thermal stratification present prior to and following closure of the Harry S. Truman Dam in both upstream and downstream reaches, and both with and without the weir. Weir construction costs were estimated to be 533K (1979$). Thermal studies predicted (a) the degree of thermal stratification likely to occur in Truman Reservoir from April through the end of August, (b) the effect of project operation on release water temperatures, and (c) possible effects of release water temperatures on existing thermal characteristics of the Lake of the Ozarks.

Using a model employing multiple regression techniques, the following predictions were made:

a. By the first week of August, Truman Reservoir will be essentially homogeneous with respect to temperature at elevation = 666 ft msl.

b. During the spring months, releases will be cooler than stream temperatures, but within the range that naturally occurs at the Truman project site.

c. Only a slight change in the thermal structure is expected in the Lake of the Ozarks.

As a result of its study, the Kansas City District concluded that the position of the crest of a weir in relation to the thermocline affects the weir's efficiency in providing epilimnetic skimming. The crest should be located well above the thermocline, minimizing the drawing of hypolimnetic water over the weir.

Bohan (1970) reported that tests were conducted on a 1:40-scale model of the water temperature control weir for the Meramec Park Dam to investigate the discharge characteristics of the weir and determine its effectiveness in preventing the release of cold water from the hypoliminion. The model consisted of a section of the approach channel, the control weir, and the intake structure. Density stratification caused by temperature differentials in the prototype was simulated in the model by using saline and fresh waters. The weir was found to be effective for containing the cold water during release of desired rates of flow of 131 to 1,028 cfs from the water supply and water quality control (joint use) pool (elevation 608.0 to 675.0 ft msl). Some withdrawal of cold water (approximately 7 percent) was observed with a discharge of 80,000 cfs and a pool elevation of 680.0 ft msl.

The results of this study and similar tests on the Clarence Cannon and West Point water temperature control weirs were used to develop a preliminary, generalized technique for predicting the effectiveness of submerged weirs.

Rock weirs were successfully employed at Stockton and Harry S. Truman projects, Kansas City District, and Clarence Cannon Dam (Mark Twain Lake), St. Louis District (Price 1990). However, all have reported low temperature and DO when the thermocline formed above the weir crest, notably during periods when hydropower generation ceased.

Leutheusser and Birk (1991) describe a weir designed to prevent the formation of improper hydraulic jumps. An improper jump is one that may become submerged and degrade into an elongated standing vortex about three to four weir heights in length. Its upstream-directed surface velocity can be comparable in magnitude to the maximum human swimming velocity of 2 m/sec. Such a force in a seemingly quiescent downstream pool is responsible for many drownings and other injuries. This jump can be prevented by increasing the height of the overflow structure in accordance with certain rules. Since the necessary structure height may become unfeasible, the jump may also be avoided by low overflow structures called baffled chute spillways, which dissipate energy by cascade action and are totally independent of tailwater conditions.

Bureau of Reclamation. BOR investigated Yellowtail Afterbay Dam in Montana by conducting extensive model studies for design development (U.S. Department of the Interior BOR 1965). The project is located at Lime Kiln on the Big Horn River about 2-1/4 miles downstream from Yellowtail Dam of the Lower Big Horn division of the Missouri River Basin Project. These studies are summarized as follows:

> Model studies to develop hydraulic design of the sluiceway and overflow weir for Yellowtail Afterbay Dam indicated the most efficient energy dissipators for each. The sluiceway has three 10-ft-wide bays separated by 2-ft tapered piers with the flow controlled by 10- by 8-ft slide gates and energy dissipated by a hydraulic jump stilling basin. It is designed for a 4,500-cfs maximum discharge. The overflow weir includes five 30-ft-wide bays separated alternately by 4- and 2-ft piers with a maximum design discharge of 15,500 cfs. Discharge is controlled by five 30- by 13.5-ft radial gates and energy dissipated by a stilling basin. Two types of energy dissipators were investigated for each structure. For the sluiceway either a hydraulic jump basin with chute blocks, baffle piers, on a solid end sill (Type III) would be satisfactory. Since an abutment wall forms one side of the stilling basin, it was decided to extend the apron and use the Type II basin. For the overflow weir the studies showed that a slotted bucket should be used. The recommended basins for both structures provided excellent energy dissipation with minor wave action and channel bed erosion. Discharge capacity and coefficient curves were prepared for both structures.

All tests were run with free flow over the weir. Simulated maximum discharge of 15,500 cfs (439 cms) was used for the tests. The discharge at this reservoir elevation was 17,000 cfs (481 cms), 1,500 cfs (42 cms) higher than the design value. The stilling basin design chosen, a hydraulic jump stilling basin, operated satisfactorily for all flows up to and including maximum discharge. Flow was smooth and well distributed with little wave action for all discharges and all tailwater settings.

U.S. Department of the Interior BOR (1994) reported its response to reports of May 1991 of high total gas saturation (117 to 122 percent) and gas bubble disease at Yellowtail Afterbay Dam by testing the different combination of flows through the various gates to obtain optimum DO and total dissolved gases. It found that total gas pressures can be lowered through a wide range of river discharges by managing the flows over the radial gates when the tailwater elevation is sufficiently high.

Folsom Dam in California discharged cold water from the hypolimnion, making it less suitable for swimming. Undesirable warm epilimnion water was released during the fall, making the watercourse less suitable for salmon migration. To alleviate both problems, existing trashracks for each penstock were fitted with shutters mounted in runners. Water could thus be withdrawn from the desired level of the water column by opening the shutters at that level. This measure could allow selective withdrawal of high-oxygen-content water from a stratified reservoir (Speece 1990).

Irrigation canals. Relining in-place water canals with concrete, then offsetting possible results of this action on invertebrate and fish populations was studied jointly with Californian and Arizonan State agencies (Mueller and Liston 1991). Artificial cover (old tires) as mitigating influences of adverse effects on biota was likewise studied for its effects on water conveyance. Artificial reefs made of used auto tires were laid in concrete-lined water canals. The experiment was located at Hayden-Rhodes Aqueduct near Parker, AZ, on mile 10 of the Central Arizona Project canal system. The water flowing in this canal can reach velocities of 1.2 ft/sec. The second site was known as the Coachella site at canal mile 34 with maximum velocities greater than 3.5 ft/sec. The reefs were made in two ways: (a) with the tires laid flat (flat reefs), and (b) with the tires positioned upright (cellular reefs).

3 Assessment of Modification Effects

Assessment of the effects of habitat-related features in tailwaters and local flood control channels have been performed by both traditional survey methods and computer-aided simulations. Selected examples of these assessment methods are presented in this chapter.

Traditional Surveys

Tailwaters

Tennessee Valley Authority (TVA). TVA has found that actual DO presented to the tailwater fishery is much greater than what is measured in turbine releases. Assimilative capacity has been determined to be related to streamflow level, natural reaeration, photosynthesis and respiration of aquatic plant communities, industrial heat loads, municipal and industrial wasteloads, oxygen demand of organic sediments, dam release DO and temperature, and tributary DO and temperature. Channel cross sections can be used to model the wetted perimeter, determined to be a primary parameter in relating biological productivity and streamflow levels.

Improvement strategies for Fort Patrick Henry Dam, for instance, included flow pulsing, aeration of the releases, instream aeration, and combinations of these (Ruane, Hauser, and Yeager 1990) to offset low DO, undesirable flow regimes, and low temperatures.

The tailwater restoration program for Douglas Dam on the French Broad River in east Tennessee provides a working example of phased-approach activities, including optimization of dissolved oxygen, improved flow regimes, biological and fishery community restoration, promotion of recreation programs, and enhanced assimilative capacity. Planning, alternative selection, demonstration, and long-term management planning illustrate a comprehensive tailwater management strategy for TVA dams in Tennessee. The phased approach recognizes that the formulation and implementation of an effective nonpoint source control strategy are crucial to comprehensive reservoir and tailwater management strategy and evaluation (McKinney, Davis, and Campbell 1988).

Yeager (1990) reported that biological monitoring by identifying and following improvements in water quality and quantity below TVA and CE dams generating hydroelectric power has provided insights into the effects of quality of dam releases on biological resources. It is feasible to monitor the biological responses to flow and DO levels at population and community levels. Multivariate analysis can discern relationships between benthic communities and physical-chemical characteristics for regulated reaches of the Tennessee River system. Moreover, such methods, while somewhat difficult in their inherent complexity, are not site-specific and therefore could be used at any reservoir/tailwater assessment location.

The South Holston aerating labyrinth weir, completed in December 1991, was the first under TVA's lake improvement plan documented to improve DO and minimum flow in the tailwater (Hauser 1993). The performance of both South Holston and Canyon Dam labyrinths was analyzed during the low DO season September-October 1992. During this period, DO is normally 3 mg/ℓ compared with the saturated value of 9 mg/ℓ. Future improvement measures are expected to achieve 7 mg/ℓ.

TVA has conducted extensive downstream evaluations to determine the degree of improvement in DO resulting from their measures attempting to improve the water quality downstream from TVA's hydropower dams. Records of temperature and DO are given for Fort Patrick Henry and Boone dams for year 1983 by Julian Day and by depth for scrollcase and forebay, respectively, as well as aeration data for Douglas and Norris dams. Data for the Clinch began in 1986, with improvement being evident in the 1990-91 season.

During the collection period, a record-breaking drought occurred in eastern Tennessee, confounding the assessment. Nonetheless, the turbine modifications brought higher DO[1] compared with other measures.

Biological impact of aeration below Norris Dam based on accepted criteria of condition of fish (trout) is reported as more positive than could be reasonably attributed to other factors. Changes attributed to the Clinch River reregulation weir are measured temperature and DO data from Clinch River Mile (CRM) 77.6 and 70.5.[2]

Corps of Engineers (CE). Bell (1971), his conclusion based upon extensive measurement and monitoring of the populations involved, stated that

> ...the creation of Bonneville Dam changed materially the natural river area under the pool. The operating levels that have prevailed since 1938 must be considered the as-is conditions.
>
> Changes during the winter period will have a minimal effect on the environment. For fisheries, rate of downward change is most important; for game birds and animals, the upper water levels during the critical periods (March, April and May) are most important."

1 Personal Communication, April 1994, T. Rizk, Tennessee Valley Authority, Norris, TN.

2 Personal Communication, April 1994, J. Ruane, Tennessee Valley Authority, Norris, TN.

The volume and operation of Bonneville pool have had little influence on the flows or temperatures of the Columbia River. An increase in fish stranding suggested that riverbed configurations should be studied and perhaps altered to minimize this problem. March water levels should be set to provide protection of game birds and furbearers during nesting and whelping periods. The effectiveness of extended-length submersible bar screens, each approximately 40 ft long, increased guidance to 80 percent for yearling chinook and well over 50 percent for subyearling chinook salmon passing at McNary Dam. In 1992, National Marine Fisheries Service tested the comparative abilities of the extended-length bar screen and standard-length submersible traveling screen to guide juvenile salmonids from turbine intakes, as well as their relative effects on fish condition. Also, WES used underwater video imaging techniques to provide information concerning fish behavior regarding the vertical barrier screen and the guiding devices (McComas et al. 1993). A study to evaluate the new juvenile salmonid bypass system was conducted by the National Marine Fisheries Services for the CE. The objectives of the study were to determine the fish guidance efficiency and orifice passage efficiency of the new bypass system installed on Monumental Dam, to determine its effect on juvenile salmonid descaling, to measure levels of smoltification in yearling chinook salmon collected in gatewells and fyke nets at different depths within the turbine intake, and to determine orifice passage efficiency within the juvenile salmonid bypass system (Gessel et al. 1993). Data acquired at Lower Granite and Little Goose dams (1985-89) suggested yearling chinook salmon were more susceptible to guidance by traveling screens than fish at intermediate stages of smoltification. However, later research at Bonneville Dam in 1988 and McNary Dam in 1991 found no significant relationship between smolt development, measured by gill sodium- and potassium-AT base levels, and fish guidance efficiency (McComas et al. 1993).

Sickel (1982) surveyed freshwater mussels in the Cumberland River from mile 30 to the confluence of the Cumberland and Ohio rivers to determine diversity, abundance, and habitat characteristics of mussels in Barkley Dam tailwaters. Proposed dredging and disposal sites were examined to estimate the potential impact of CE activities on the mussels. Extreme daily fluctuations in discharge through the dam and high silt loads were predicted to have an adverse effect on reproduction and host fish distribution; therefore, monitoring was recommended.

Walburg et al. (1981a,b,c, 1983) summarize field investigations conducted at seven reservoirs in 1979 and 1980 to determine the effect of reservoir releases on tailwater biota. The study sites differ greatly in project purpose, depth of water release from the reservoir, and location. They are typical of many CE reservoirs throughout the United States. Studies were conducted in tailwaters below both flood-control and peaking hydropower projects.

Effects of reservoir discharge were most evident near the dams where environmental stress was most severe; farther downstream the effects were moderated. The invertebrate and fish communities in tailwaters were affected mostly by the temperature, volume, and timing of the discharges. High levels of iron and manganese occurred in most tailwaters, but their effects on invertebrates and fish were not addressed in this study.

The numbers of invertebrate and fish species were largest in tailwaters of flood-control projects with warmwater release and smallest in tailwaters of large hydropower projects.

As reported by Swink and Jacobs (1983), an impoundment on the Green River, Kentucky, altered the respective fish communities both below the dam and in the unregulated river above the reservoir. Reservoir species apparently migrated both downstream and upstream out of the reservoir and were abundant in both areas. Abundance in the tailwaters of two species common in the reservoir—white crappies (*Pomoxis annularis*) and gizzard shad (*Dorosoma cepedianum*) — was positively correlated with the volume of discharge. Redhorse (*Moxostoma* sp.) and catfish (Ictaluridae) were less abundant in the tailwaters than above the reservoir. Postimpoundment reductions in abundance of minnows (Cyprinidae), redhorse, and catfish in the tailwaters appeared to be related to lower water temperature caused by discharge of water from the hypolimnion.

Swink and Jacobs concluded that using a stream station above a reservoir to represent the preimpoundment fish community will lead to erroneous conclusions for species that migrate extensively upstream after becoming established in the reservoir. However, comparisons may be valid for species that seldom move upstream.

Factors that alter the relative abundance of tailwater fishes were identified by Jacobs et al. (1985). Specifically, the objectives of this study were as follows:

a. Determine the significance of fish recruitment from the reservoir into the tailwater.

b. Determine which species are recruited from the reservoir.

c. Identify conditions in the tailwater that foster the concentration of fish.

d. Identify the season of recruitment.

e. Describe direction and season of movement of tailwater fishes.

To meet these objectives, fish were intensively sampled, marked, and recaptured in the immediate tailwater of Barren River Lake, Kentucky, for a 1-year period. Analyses of the resulting data indicated that the reservoir may be the source of recruitment for the most abundant fish species in the tailwater of deep-release, flood-control reservoirs.

Tate (1982) presented the results of gas transfer tests of the outlet structure at Enid Lake, MS. Radioactive tracers, krypton-85, and tritium were used to determine the gas transfer characteristics of the outlet structure. The sampling technique isolated the effects of the outlet conduit, the trajectory between the conduit and the tailwater, and the submerged portion of the stilling basin. DO measurements were taken in the conduit in an attempt to supplement the radioactive tracer data.

Dortch, Tillman, and Bunch (1992) analyzed the results from field studies of water quality downstream of reservoirs to obtain an improved understanding of the mechanisms and chemical transformations occurring in reservoir tailwaters. The research focused on the poor water quality (e.g., low dissolved oxygen and increased concentrations of reduced substances, such as iron, manganese, and sulfide) associated with deep, anoxic releases from hydropower and nonhydropower dams. In some cases, the analyses confirmed kinetic models that describe the change in constituent concentration with time and resulted in relationships to estimate kinetic rate coefficients. Results were used to develop a model of tailwater quality (Tillman, Dortch, and Bunch 1992), and the model was validated with data from the field studies.

Koryak and Hoskin (1994a,b) report that

> Spring and autumn electro-fishing surveys were conducted in the tailwaters of 16 CE reservoirs in the upper Ohio River drainage basin of northern West Virginia, western Pennsylvania and northeastern Ohio between 1986 and 1990. The single most important variable influencing the fisheries appeared to be water quality. Reservoirs in the glaciated portion of the Appalachian Plateau had higher nutrient concentrations and plankton densities, with subsequently productive tailwater fisheries. Tailwaters in the unglaciated plateau were substantially less productive, and those impacted by drainage from bituminous regime tailwaters were lower than that of cool and warmwater outflows ... these trout waters are nonetheless generally perceived to be of high quality. At most of the tailwaters examined, fish exported from the upstream impoundments were significant elements of the outflow fisheries. Intense water resource engineering development along one stream appeared to negatively influence fish diversity but not productivity over its entire drainage.
>
> The presence and height of stilling weirs below the dams very significantly influenced the local distribution and abundance of fish. While structure was abundant and complex at all of the study sites, the presence of tailrace embayments at two projects contributed greatly to the productivity and diversity of their fisheries.

A report of a 1986 electrofishing effort upstream and downstream, respectively, of a stilling weir showed the catch downstream of the weir (Mahoning Creek Dam stilling weir) to be over 18 times, by weight, of the catch upstream from the weir.

U.S. Fish and Wildlife Service. The U.S. Fish and Wildlife Service (Kentucky) assessed the effects of a flood-control reservoir on downstream macroinvertebrates by comparing the tailwater community with that of a natural stream (Novotny 1985). Samples were collected 1.6 and 21.1 km below Barren River Lake dam in 1979, 1980, and 1981 and in a reservoir tributary in 1980 and 1981. Dominant macroinvertebrate taxa in tailwaters were primarily small organisms with a high tolerance for dynamic living conditions. Of these, aquatic *Diptera*, *Oligochaeta*, *Caenis*, *Cheumatopsyche*, and *Planariidae* were most common. The effects of reservoir discharge were most evident near the dam, where macroinvertebrate densities were relatively high and taxonomic diversity was low. Downstream, the impact of the reservoir was moderated, but recovery was judged incomplete.

Fish abundance and population stability were compared in the tailwater and in an unregulated tributary of Barren River Lake, a flood control reservoir in Kentucky. The abundance of fish was greater in the tailwater near the dam and was dominated by gizzard shad, bluegills, and white crappies. Three riverine suckers were less abundant in the tailwater than in the unregulated stream. Fish populations in the tailwater were less stable than those in the stream (Jacobs and Swink 1983).

State stocking records for tailwater trout are used to determine what role tailwaters play in each State's trout management program. Of the fisheries surveyed in 16 southern States, data indicate that 48 tailwaters in 13 states were stocked with trout during 1980. Of the 3.7 million trout in these waters, about 81 percent of them are of catchable size and about 19 percent are fingerlings (Swink 1983).

Swink and Jacobs (1983) report that an impoundment on the Green River, Kentucky, altered the fish community below the dam and in the unregulated river above the reservoir. Reservoir species apparently migrated both downstream and upstream out of the impoundment. Abundance of two species common in the reservoir, white crappies and gizzard shad, was positively correlated with the volume of discharge. Postimpoundment reductions in abundance of minnows, redhorse, and catfish in the tailwaters appeared to be related to lower water temperatures caused by discharge of water from the hypolimnion.

Non-Federal. The epilithon in the Glen Canyon tailwater, which underlies the Glen Canyon Dam on the Colorado River, is dominated by the chlorophyte *Cladophora glomerata*. The littoral epilithon is especially important to other trophic levels in aquatic ecosystems, providing habitat for fish and macroinvertebrates. Because flow releases from the Glen Canyon Dam determine the exposure regime for the littoral epilithon, the effects of atmospheric exposure of the epilithon on chlorophyll *a* and biomass were investigated. The experimental protocol is described. Results indicated that chlorophyll *a* was much more sensitive to atmospheric exposure than biomass. Exposure to solar radiation was the most important determinant of mortality. Although epilithon from the permanently inundated zone was as much as 10 times more productive, it had an assimilation ratio similar to that of the epilithon from the fluctuating flow zone. The gross primary production of the algae appeared to be a constant function of the amount of chlorophyll *a* present (Angradi and Kubly 1993).

Stanford and Ward (1984) studied the physicochemistry and biotic structure at 11 sites along the altitudinal profile of the Gunnison River to determine if the ecosystem response to stream regulation by hypolimnial release dams followed any quantifiable pattern. Cold, stabilized flows from the dams have eliminated many species from the tailwater zoobenthos (as is usually the case below hypolimnial release dams), but community structure has recovered (or reset) farther downstream. The lotic community at a point approximately 80 km downstream from the last dam in the lower reaches of the river continuum resembles the community that existed in an upstream segment before regulation. This downstream ecological shift may be partly explained by phenomena involving fluvial mechanics, temperature, and nutrient cycling.

Binns (1986) evaluated changes in trout habitat in the Hog Park Reservoir tailwater in Wyoming. This impoundment was formed beginning in 1965 as a storage reservoir for a water diversion from the North Fork Little Snake River by the City of Cheyenne. By 1973, it supported a trout population of 81 lb/acre. In the early 1980s, the project was enlarged, resulting in large quantities of sediment being washed into the tailwater of the stream. Binns compared the trout habitat conditions before and after the enlargement of the dam, a 10-year period. The trout habitat was evaluated in August 1975, 1.4 miles downstream from Hog Park Dam, the same site used by Wesche (1973). Annual streamflow and late summer streamflow were obtained from Cheyenne streamflow records. Binns (1979, 1982) Habitat Quality Index (HQI I and II) was used to calculate habitat value. Using these procedures and tools, Binns concluded that habitat conditions had deteriorated drastically in the time period examined for several reasons:

a. Although water temperature, nitrates, fish food, and stream width were about the same, and fish food organisms, mostly in sects, had slightly increased, the stream rating had not changed and shelter areas for trout decreased.

b. Shelter areas, such as undercut banks and deep pools lost due to increased sediment, decreased by 79 percent. This loss represents serious degradation of habitat, thus lowering the carrying capacity of the stream for trout.

c. The physical substrate changed from mainly a gravel and small cobble mix with occasional small sand and silt bars present, with small amounts of fine sediments found around rocks to mostly sand and gravel by 1985—most of the stream was rated as sand and gravel.

d. Streambanks became less stable, with eroding banks increasing from 15 to 26 percent in the 10-year period examined.

e. Stream discharges resulting from the increases in erratic discharges, the ASFV (peak yearly discharge divided by the minimum flow) was relatively steady from 1969 to 1974. From 1979 to 1984 it had a significantly different increase. A "t" test showed no difference between the two periods, revealing that the variability observed was due to a change in water releases and not due to the total water in the channel.

Streambeds

The basin flow model of Singh and Broeren (1989) provides the hydraulic data necessary to apply the Instream Flow Incremental Methodology (IFIM) of the U.S. Fish and Wildlife Service. Using the basin hydraulic geometry relations derived from the U.S. Geological Survey current-meter flow measurements, width, depth, and velocity can be shown as simple power functions of discharge at a given cross section (Leopold and Maddock 1953). The weighted usable area can then be derived to quantify suitable stream habitat linked to flow conditions throughout the basin.

Corps of Engineers (CE). Personnel of the Pittsburgh District compared a biological survey performed in 1975 of a channel that had been excavated to a broad, flat trapezoidal shape to unmodified pool and riffle portions of Tenmile Creek. The excavated channel was found to be more unlikely to have benthic colonization when compared with the more "natural" reaches. Improvements to the excavated channel were recommended that were intended to imitate natural local stream riffles. The channel was designed to have a stream depth of less than 1 ft 90 percent of the time.

Unfortunately, after the project was completed in 1979, roughly half of the low-flow channel filled with sediment, particularly in parts of the channel with more moderate slope. Most of the sediment deposited was bituminous coal mining spoil, suspected to originate from the washout of one large spoil pile by way of a tributary (mile 10.53) to Tenmile Creek. The current study reexamines the channel experimental design concepts, recognizing that the anticipated aquatic life benefits may not have been realized, and documenting the effectiveness and deficiencies to define expectations of the Marianna LFPP experiment more realistically. To this end, results of electrofishing surveys conducted in 1975 and 1988 were compared (Koryak and Hoskin 1994a,b).

Calhoun, Beitinger, and Zimmerman (1982) reported that acute selected temperatures at acclimation states of 10, 20, and 30 °C were significantly different ($P < 0.05$) between red shiners (*Nutropis lutensis*) from an unregulated stream and those from a stream below a hypolimnion-release reservoir in north-central Texas. Estimated final temperature preferences for the two populations were 30.0 and 23.3 °C, respectively. These results support the hypothesis that temperature selection behavior in this species is mutable and subject to regulation by natural selection. The authors hypothesize that the lower thermal preference of tailwater populations represents an adaptive response to a depressed thermal regime typical of hypolimnion-release reservoirs.

As reported by Matter et al. (1983), the Savannah River below Lake Hartwell, Georgia-South Carolina, receives hypolimnetic water discharged from the reservoir for peak power generation. Invertebrates and particulate organic material (POM) in the water column were collected during a 24-hr release cycle at sites 1.0, 4.5, and 12.5 km downstream from the dam. Water released during generation reached a maximum discharge of 688 m^3/sec. River discharge was less than 10 m^3/sec during nongeneration periods. Highest POM concentrations were associated with the initial downstream surge of water at the start of power generation; values were 200 to 400 times greater than those during nongeneration periods. Of the drifting invertebrates, 80 to 93 percent originated in the reservoir; the rest, primarily Oligochaeta, Diptera, and Ephemeroptera, were from the tailwater.

Corps of Engineers (with U.S. Department of Agriculture). In the Demonstration Erosion Control (DEC) Project in the Butupan Bogue Creek near Grenada, MS (Knight 1991), three protection measures and a control were employed, each consisting of three replicates of old lateral dike sections, new lateral dike segments, transverse dike sections, and natural bank reach.

Catch was higher along transverse dikes than along either lateral dike but was not different from the natural bank controls. No differences in species diversity were observed. Poorest catches were associated with old lateral dikes with catch per unit of effort significantly lower along old lateral dikes than all other bank types. Scour holes probably do not affect fish production directly but provide additional area capable of supporting both larger fish and greater numbers of fish. If not for these scour holes, larger fish would have to seek deeper water downstream, particularly in times of low flow. Since costs for the two dike types are the same, transverse dikes provide an environmentally sound, cost-effective way to protect and to stabilize the banks.

DEC researchers observed that in only one growing season woody cover increased from 38 percent to 666 percent of bankline (Shields, Cooper, and Knight 1993). Individual plantings did about one-half what was expected because of competition from kudzu vines. Length of fish and numbers of fish doubled and total weight of fish per unit of effort increased about tenfold. The study site was located in Hotophia Creek in the Yazoo River basin below a drainage area of 90.9 sq km. Materials used for stabilizing the banks were principally dormant willow posts, planted with the bud end upward. Only one-third of the posts set out in the trial planting survived flooding, but those that remained flourished. The stage levels after implementation of these techniques are documented in Abraham and Sutton (1993).

Bureau of Reclamation (BOR). Mueller and Liston (1991) reported habitat enhancement resulting from reef placement in irrigation canals in Arizona. Species diversity compared with canals without this cover (controls) increased by 140 percent, fish density 20 times, and fish biomass 10-fold. Fish densities increased sharply along with vegetative biomass. If vegetation biomass had been enhanced, fish densities would probably have been greater. Cover-oriented fish (largemouth and smallmouth bass, flathead catfish) predominated.

Reefs increased the abundance of all major fish species except channel catfish. Enhancement generally did not reach the levels measured in the earthen sections (as opposed to concrete sections) with the exception of black bass, which was greater than that for the earthen canal. Reefs greatly enhanced the fish community and to a lesser extent the invertebrate community while not effecting an adverse impact on the hydraulic characteristics of the concrete-lined canal.

Computer-Aided Simulations

In isolation, the highly "applied" nature of modeling water quality of reservoir tailwaters, and, by extension, regulated rivers, may seem only tenuously associated with traditional limnological endeavors. However, modeling studies can serve to integrate the specialities of limnology, biogeochemistry, ecology, hydrology, meteorology, hydraulics, and hydrodynamics. Water quality modeling of tailwaters, regulated rivers and streams has its greatest value in determining relative impacts of various operational alternatives (Zimmerman 1988).

Modeling the relationship between channel modifications/structures and aquatic habitat potential, aided by a computer, permits comparison of several plans that would be unwieldy, unfeasible, and prohibitively costly to model physically. Instead, this tool allows the resource planner to anticipate cause-and-effect, to explore many options to arrive at the "optimum" measure. This distinct advantage has spawned a wide variety of computer models relating to exploring the effects of structures influencing water quality and aquatic habitat. For example, the Environmental Protection Agency's Storm Water Management Model (SWMM) provides dynamic routing of storm water runoff (Wang and Williams 1989). Willey (1988) includes in the Water Quality 1988 seminar proceedings a water temperature prediction model for the Columbia River system.

The formula of Kobus (1968) was used to estimate the success of the air bubble diffusers at Allatoona Reservoir in Georgia and Lake Casitas in California. After installation of the aeration device, dye methods were used to determine the upwelling flow. The dye dilution measurement yielded higher figures than the estimates according to Goossens (1979) and Kobus (1968), but they agreed in general magnitude (Hauser and Bender 1990; Yeager 1990; Spain and McKinney 1990).

Hauser et al. (1983) report their evaluation of downstream improvements in DO, which can be anticipated as a result of different levels of aeration at Cherokee and Douglas dams. The report describes (a) field studies undertaken to describe late summer conditions for model calibration and verification, (b) development and calibration of unsteady flow and water quality models for the tailwater reaches from Cherokee and Douglas dams to the Holston and French Broad river confluence at the head of Fort Loudoun Reservoir, and (c) model predictions of DO in the tailwater reaches and at their confluence (after mixing) with and without aeration. The most influential factors affecting downstream DO are flow magnitude, natural reaeration, and photosynthesis/respiration of aquatic macrophytes. When DO in turbine discharge is low in the late summer, long periods of high turbine discharge move low DO water downstream more quickly. The shortening of residence times in the reservoir reduces the effects of natural reaeration and photosynthesis on DO concentrations. Therefore, the worst case is full turbine discharge of low DO water. DO reaches a minimum during the night just after turbine shutoff, principally because of the difference in photosynthetic rates. This differing rate of photosynthesis is superimposed on an unsteady flow regime, diurnal variations of DO, and temperature. The water quality model used in this study predicted temperature, biochemical oxygen demand (BOD), and DO as a function of longitudinal location and time with respect to hydraulic, meteorological, and inflow conditions. The unsteady flow model provided flows, mean depths, and surface widths. The heat budget model required as input hourly time series of dry bulb temperature, dew point temperature, wind speed, solar radiation, and inflow temperature. The model was formulated from the one-dimensional mass transport equation, solving for, in order, temperature, BOD, then DO. The upstream boundary condition in the calibration of the model for temperature, DO, and BOD was the measured time series temperatures for the scrollcase, scrollcase DO, and scrollcase BOD. For simulations, the upstream temperature was held constant, a DO level based in assumption of aeration or seasonal release DO and constant BOD.

Conclusions of the above model study include the following:

a. Flow magnitude is the most important factor governing DO.

b. Any amount of DO added at the tailwater is diminished as the water moves downstream. Any increase in DO downstream is due solely to natural reaeration.

c. Aeration was required at both dams to maintain 5 mg/ℓ downstream. Aerating at only one dam was insufficient, regardless of the level.

General guidelines based on the effects downstream of reservoir releases, in many cases based on quantitative models, have been developed and applied to assess the impacts on tailwater biota (Nestler 1987). Table Rock Dam tailwaters were the subject of a modeling study conducted to assess the effects of a selective withdrawal structure. Placed in front of two ports, it was evaluated for its capability to improve water quality and to enhance trout habitat by maintaining the outflow temperatures below 17 °C and increasing DO concentration. Model results identified a method that would both maintain DO at or above 4 mg/ℓ and meet temperature requirements (Hamlin and Wlosinski 1988).

The SELECT model was employed with success by the Tulsa District CE to predict release characteristics and low levels. Late summer fish kills associated with high temperatures, low DO, and fish entrapment occasionally occur in the tailwaters of the Tulsa District CE project lakes. Using the information gained from using the model with input data relating to two lakes, Eufaula Lake and Fort Gibson Lake, the Tulsa District controlled releases such that fish kills were avoided (Nolen, Carroll, and Veenstra 1988).

Fish facilities at the Belleville weir on the Loire River, the Bergerac Dam on the Dordogne River, and the Golfech powerhouse on the Garonne River were optimized by the use of hydraulic model studies at the "Institut de Mecanique des Fluides" at Toulouse. In the first two fishways, flow conditions, i.e., flow velocity, drop between pools, and rate of energy dissipation per unit of volume, were studied in relation to tailwater and headwater fluctuations. The main purpose of these studies was to optimize the position of entrances and determine the discharge needed to provide adequate attraction at these sites. The modeling resulted in design changes that should improve fish passage (Trivellato and Larinier 1987).

Reliable tools yielding consistent results are required to explore alternative reservoir operating plans. In order to determine the operating plan(s) producing minimal aberrant water quality downstream, a PC-compatible tailwater quality model (TWQM) that performs well for DO, dissolved manganese, nitrogen species, and total dissolved sulfide for the data collected at four reservoirs was developed (Martin and Dortch 1987; Tillman, Dortch, and Bunch 1992). The 1992 model was applied to data for Lake Greeson, Nimrod Reservoir, Rough River Reservoir, and Canyon Reservoir, performing well with its predictions.

Nestler and Schneider (1992) presented a method for predicting temperature patterns downstream from a peaking hydropower dam to revise and update systemwide reservoir operations manuals. A one-dimensional model simulated temperatures at about 1-mile intervals with this output, then evaluated using linear and nonlinear equations of "best" fit.

Nestler, Schneider, and Hall (1993) evaluated alternatives using a mathematical model applied to the Missouri River. They developed a screening model depicted by a series of computer algorithms, comprising a two-step process for weighing respective courses of action regarding reservoir releases. Downstream water temperatures were simulated for 108 scenarios of stratification, hydropower peaking patterns, and meteorological conditions. The output was then analyzed statistically to identify trends and patterns in the results. Prediction of tailwater conditions in this fashion offers the most unbiased assessment of cause-and-effect relationships between hydropower releases and downstream environmental conditions.

Since a need exists to predict the water quality and habitat suitability in response to a proposed action, many models have been developed and used as aids in evaluating such action(s). Such applications are, of course, most frequently applied to possible impacts an action might have on fish habitat. Miller et al. (1991) report, "The Instream Flow Incremental Methodology (IFIM) was used to evaluate instream fish habitat in the Platte River in central Nebraska. The IFIM analysis .. incorporates 1) water temperature modeling and water quality, 2) fish species composition and distribution, 3) physical habitat data and 4) 43 years of flow records. The Platte River system has competing water demands from hydropower, agricultural irrigation, municipal uses, recreation and most recently from recommended instream flows for fish wildlife resources..."

IFIM was employed for the CE Nashville District to quantify the effect that the uprating of the Wolf Creek Dam powerhouse would have on the downstream habitat of rainbow and brown trout. IFIM predicted that habitat availability for adult rainbow and adult trout would decrease if uprated conditions with associated low and average flows, while under high flow, habitat for adult stages would increase. Habitat conditions for juvenile trout were negligible under both existing and uprated conditions (Nestler et al. 1988).

New Mexico State University and New Mexico Department of Game and Fish developed a computer model, RIOFISH, which accomplishes many analytical tasks as a sportfishing planning tool. The model links hydrologic, biologic, and economic components into a mathematical representation of fish habitat, fish population dynamics, and angle effects. Hydrology is based on mass balance; the biology is driven by discharge, water surface area, nutrient concentrations, and water exchange rates from the hydrology model and other outside factors. The economic component predicts angler effort using water quality, fish biomass, onsite improvements, and the spatial distribution of travel costs from angler origin to site destination. The hydrologic submodel is complete for eight reservoirs and tailwaters in the Rio Grande Basin; three reservoirs and tailwaters in the Canadian river system; four reservoirs and tailwaters in the Pecos River system; and one reservoir and tailwater in the San Juan River system. The completed model will include 18 reservoirs and their tailwaters when Red Bluff Reservoir is added to the Pecos River and Bluewater Reservoir is added to the Rio Grande Basin. RIOFISH offers managers improved economic performance measures of potential decisions (Cole et al. 1990).

Several habitat-based methods are available to relate flow to fish habitat value (Reiser, Wesche, and Estes 1989). The most commonly applied methodology, the Physical Habitat Simulation System (PHABSIM) of the IFIM, developed by the U.S. Fish and Wildlife Service (Milhous, Updike, and Schneider 1989), has received criticism for some applications, particularly on warmwater river systems (Bain and Boltz 1989). The primary criticism stems from the fact that development of a single index that relates the value of a particular alternative to an entire fish community is nearly impossible using suitability curves as the basis of the analysis. To do so would demand that the flow requirements of each life stage for each species be determined, summarized, and integrated.

While the use of suitability information to define the habitat requirements of fishes does not seem to be technically desirable or logistically possible in all cases, sufficient information is available to suggest that fishes respond to depth and velocity patterns (Bain, Reed, and Scheidegger 1991). In fact, Bain, Reed, and Scheidegger (1991) point out that the distribution of warmwater fishes in the Cahaba River system of Alabama, a large warmwater river system, can be largely explained using broad depth and velocity categories.

Most population- and community-level studies are currently conducted using habitat-based evaluation techniques. Community-level interactions, such as competition and predation, are assessed by incorporating resource partitioning indices into the habitat-based approach. This type of approach is suited to a fishery biologist but not an engineer, and requires resources not typically available for a channel modification or flood control project. For this reason and others, community-level studies are seldom undertaken by the CE.

A relatively new approach, the Index of Biotic Integrity (IBI), can be used in a variety of ecosystems to document the importance of aquatic assemblages. The IBI uses an index reach to develop a combination of matrices designed to reflect insights from individual, population, community, ecosystem, and zoogeography perspectives (Miller et al. 1988).

Means of assessing the effect of a channel modification on habitat have been described (Nestler 1993). Based on an assessment of the deficiencies of existing habitat assessment techniques, the Riverine Community Habitat Assessment and Restoration Concept (RCHARC) (Nestler, Schneider, and Latka 1993) was formulated.

RCHARC offers three distinct advantages over existing methods:

a. Implicitly uses an ecosystem or community-based approach to assess habitat quality rather than a species-based approach, which makes it more suitable to warmwater systems than existing methods.

b. Presents requisite channel conditions in terms the design engineer understands, that is, cumulative distribution of depth and velocity.

c. Relieves the investigator of the task of developing life stage-specific suitability curves for each species.

While good predictions have been achieved with models developed thus far, it remains for these modeling techniques to be applied in other hydrologic and geographic regimes. In a study of Nestler, Schneider, and Latka (1993) employing RCHARC, relationships were developed between flow and habitat values, enabling the Missouri River Division personnel to predict water quality downstream of Gavins Point Reservoir. A systematic concept to analyze the effects of river and tailwater operations on physical habitat for native riverine fish, the RCHARC relates the effects of flow alterations on aquatic biota. The system combines conceptual elements of the IBI (Karr et al. 1986; Bickers 1988) and PHABSIM (Milhous, Wegner and Waddle 1984; Milhous, Updike, and Schneider 1989).

RCHARC requires the use of a river system as the basis of comparison, that is, a "comparison standard" for the analysis against which the various project alternatives can be evaluated. The comparison standard river system (CSRS) is considered to represent the ideal habitat conditions, both in terms of channel configuration and seasonally varying flow characteristics, for the aquatic community in the project river system. Data collected normally includes cross-sectional profiles, discharge, depth and velocity pairs, dissolved oxygen, water temperature, thalweg and water surface elevation profiles, supended sand bed load sediment, and armor layer and substrate samples (Abt et al., in preparation).

Summers, Wilson, and Kou (1993) present a method to compare water quality models configured to represent different levels of spatial, temporal, and mechanistic complexity. Models are compared using the results of model uncertainty results using the Wilcoxon ranked sum test.

4 Summary

Man-made impoundments formed when erecting dams usually cause modification of water quality (and aquatic habitat) in the tailwaters immediately downstream. These tailwaters have been recognized as having as great (or greater) a sports fishing potential as the main impoundment above them. As reported in Chapter 1, many Federal agencies have used local features and structures to enhance aquatic habitat, specifically fish habitat. The expansion of other recreational uses (camping, hiking, water-skiing, and other water sports) is a logical next step when water quality supporting sports fishing is improved. Therefore, the public use and perception of a resource is greatly enhanced by maintaining water quality and conditions ensuring desired aquatic habitat.

Because so much value is placed on high quality aquatic habitat, modifications to enhance aquatic habitat have been employed by all Government agencies having projects altering natural streamflow. These modifications include no action, operational modification, selective withdrawal, and structural modification (hub baffles, etc.). Conspicuous modification methods include weirs, localized mixing/aeration, streambed modification, and timed releases to accommodate the desired activity or purpose.

Some streambed modifications are relatively inexpensive ways of increasing habitat by increasing the surface area available to aquatic biota, usually resulting in minimal disruption to the stream channel flow. Many of these channels serve as high-density floodways or as irrigation canals, so flow disruption by the habitat enhancement measurements must be minimal. Such techniques have been employed with considerable cost-effective success.

Tailwater management may include the use of weirs as "passive" aerators to maintain streamflow, temperature, and dissolved gases at prescribed levels. Many designs are currently being used that offer varying levels of success. Both U.S. Federal agencies and foreign governments have employed weirs to enhance water quality as well as for other purposes. For example, TVA, probably the most widely experienced of Government agencies in mitigating adverse impacts to downstream habitat of their hydropower projects, reported in 1984 the successful use of compressed air and other alternates to weirs and hub baffles, in eight projects, improving the downstream flow regime and water quality. Particular success was demonstrated in the improvement of DO and temperature resulting from the water quality improvement measures above, below, and at the turbines of their hydropower plants.

Methods of assessing the effectiveness of the various measures to improve aquatic habitat include both traditional field methods and computer simulation. Parameters influencing the quality of aquatic habitat include DO, wetted perimeter, streamflow level, reaeration, photosynthesis and respiration of plant communities, heat loading, and BOD. Improvement of any or all of these parameters by a proposed measure can be readily quantified with traditional field assessment techniques. Computer-aided simulations of various kinds are frequently used by the various agencies to predict the probable results of a particular action. These tools give the planner a great advantage in that he can assess the effect of a proposed action without expending the resources necessary for other forms of assessment, such as physical models, etc.

No one procedure or group of procedures can be identified as "best" for promoting better aquatic habitat at or near a project regulating streamflow, but the experiences of the agencies mentioned herein point to certain generalizations regarding candidate measures.

Certain relevant steps in the study of the proposed habitat-improvement measure are advised. On a practical level, the first question may be "Will this measure compromise the project? If so, how and how much?" Next, "If there is a compromise to the stated purpose of the project, how can this loss be offset?" For instance, if decreasing streamflow to improve downstream habitat/recreational suitability will result in a substantial loss of merchantable power, can this cost be recovered by charging user fees as was done in the case of the Ocoee River in Tennessee and Georgia (Speece 1990)?

Next, the nature and degree of aquatic habitat enhancement expected to result from the addition of a feature and structure should be predicted in terms of benefits/tradeoffs. Aquatic habitat should be surveyed both before and after the action to check the reliability of the predictions. Techniques for making the predictions may then be adjusted so that results of the model are consistent with the actual outcome, and will be better "tuned" when next applied.

Various agencies have used both traditional and computer-aided means to assess the condition of the aquatic environment of tailwaters and local flood control channels, particularly to determine the efficacy of specific measures to improve water quality degraded by man-made structures and operations. The economy realized in using the various computer models exclusively, or in conjunction with other techniques, to predict the resulting habitat quality given a particular operational or structural change is becoming well recognized.

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13. ABSTRACT *(Maximum 200 words)*

Man-made dams usually result in modification of water quality (and aquatic habitats) in the resulting impoundments and in the tailwaters immediately downstream. These tailwaters have as great a sports fishing potential and other recreational potential as the main impoundment. Therefore, the public use and perception of this resource are greatly enhanced by maintaining water quality and conditions ensuring desired aquatic habitats. Various methods designed to promote desired habitats have been employed by Government agencies having projects altering natural streamflow. Streambed modifications are relatively inexpensive ways of increasing habitat by increasing the surface area available to aquatic biota, usually resulting in small disruption to the stream channel flow. Many of these channels serve as high-density floodways or as irrigation canals, so flow disruption by the habitat enhancement measurements must be minimal. Such techniques have been employed with considerable, cost-effective success.

Tailwater management may include the use of weirs as "passive" aerators to maintain streamflow, temperature, and dissolved gases at prescribed levels. Both U.S. Federal agencies and foreign governments have employed weirs, modified power generation operation, and forced oxygen below surface impoundments to enhance water quality and for other purposes.

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Computer-aided simulations have been employed and give the planner a great advantage in that he can assess the effect of a proposed action without expending the resources necessary for other forms of assessment, such as physical models, etc. No one procedure or group of procedures can be identified as "best" for promoting a better aquatic habitat at or near a project regulating streamflow, but the experiences of the agencies mentioned herein point to certain generalizations regarding candidate measures as to benefits/tradeoffs.

Finally, an aquatic habitat should then be surveyed to check the reliability of the predictions to "tune" the next iteration.

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Streambeds
Stream modifications
Tailwater
Weirs